Regional climate modelling in the European Alpine region with focus on simulated precipitation and subsequent hydrology

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Abstract

Global climate and its change has to be investigated and assessed on the regional and local scale, where societies are essentially affected by ambient meteorological conditions. Global climate models (GCMs), however, are still too coarse to give reasonable information at correspondingly high horizontal resolutions. Thus, methods of so-called 'downscaling' have to be devised and applied to bridge the gap between coarse GCM resolution and the required fine scale meteorological information in the regions of interest. This is particularly true for areas with complex fine scale features of orography, land use and soil types, such as the research area of this study, the upper Danube catchment. This region is located mainly in the southern part of Germany and western Austria, extending fairly into the European Alps. Here, near surface meteorogical data has to be provided to a set of subsequent climate impact models on an extremely high resolution of 1 km.

The present study focusses on regional climate modelling that resorts to the physically based meteorological limited area model MM5 for the purpose of downscaling long time global climate simulations. MM5 is operated on a 45-km grid over Western Europe and is driven by observation based data or GCM output at the lateral boundaries of its model domain. In a second downscaling step the RCM output data are further processed with a statistical downscaling algorithm to the required resolution of 1 km.

Current studies on regional climate modelling seem to lack a comprehensive evaluation of the overall GCM-RCM model chain with a clear separation of model deficiencies of the global and the regional model, respectively. The present work in this sense complements existing literature with a two-step evaluation procedure, concentrating on simulated precipitation in mountainous terrain. In the first step the regional model is driven with 'optimal', observation based meteorological input data (ERA40 re-analysis). In a set of sensitivity experiments an optimal configuration of MM5 is identified. This set is spanned by three convection schemes to get an estimate of the possible range of simulated precipitation amounts inherent to the MM5-system. Furthermore, two different formulations of the horizontal numerical diffusion are investigated with respect to their influence on simulated precipitation in mountainous terrain. It is found that the impact (on simulated precipitation) of the formulation of numerical diffusion is similarly large as the sensitivity to the convection scheme. A reference experiment with the optimized configuration of MM5, comprising the years of 1991 to 2000, shows reasonable correspondence to observations. Also the mean monthly diurnal cycles of near surface temperature and dew point temperature verified in the Alpine foreland compare quite well to station data, showing some minor discrepancies mainly in the afternoon that seem to be common to regional models. In the second step the performance of the GCM-RCM approach is investigated using two long time simulations for the years of 1971 to 2000, switching from observation based input fields to the output of a global climate model (ECHAM5). Using an ECHAM5 present day climate simu-

lation as driving data induces excessive overprediction of precipitation by up to 80 % in the colder seasons, primarily over the Alpine slopes. The large scale flow provided by the global data sets reveals moderate differences indicating an increased number of low pressure systems travelling from the Atlantic into the Alpine region for ECHAM5 compared to ERA40. Partitioning 3-hourly 700 hPa winds according to direction and speed in the central Alps specifically shows a distinct shift to stronger westerly and north-westerly winds. Furthermore, aggregating 3-hourly rainfall amounts to the same wind direction and wind speed intervals reveals strongly intensified precipitation due to the overly intense westerly winds.

To overcome the current deficiencies in simulated precipitation, imposed by the driving GCM, a systematic climatology based bias correction is applied to the RCM output. The bias correction is implemented within the subsequent statistical downscaling algorithm, that was further refined in the course of the present study. The overall meteorological model chain (GCM-RCM and statistical downscaling) is evaluated from the view of subsequent hydrological (impact) modeling. Under ECHAM5 conditions the application of the bias correction proves essential for realistic simulations of mean monthly discharge values as well as daily discharge spectra in the upper Danube catchment. Without bias correction the surplus precipitation in the colder season leads to massive overprediction of corresponding discharge values.

With the two-stage downscaling procedure an IPCC A1B global climate change scenario for the 21st century (simulated with ECHAM5) is exemplarily processed for the upper Danube catchment. To put the results based on MM5 in perspective also results relying on a different regional model (named REMO), processed in an identical manner, are considered. Both downscaled datasets agree in an overall rise of near surface temperature with a particularly noticeable wintertime warming of up to 5–7 K towards the end of the century. Relatively higher changes are found for the elevated areas. For precipitation the picture is considerably more complicated. The high resolution datasets agree, however, in substantial rainfall deficits in summer of roughly -30 % according to the long time linear trend over the whole century.

Last but not least MM5 is coupled in a fully two-way interactive mode to a high-resolution (1 km) landsurface-vegetation-hydrology model to benefit from its sophisticated formulations of inner-soil transport of moisture and its highly detailed algorithms of evaporation by plants. Furthermore the new scheme relies on highly differentiated, high resolution classifications of soil- and landuse-types. With this new model composite highly realistic results in terms of precipitation and near surface temperature in the upper Danube catchment (simulation period 1996–1999) could be achieved. The bias of mean annual precipitation could be reduced to +5 % compared to +13 % of the original MM5. The cold bias of 0.9 K in mean annual near surface temperature was almost eliminated (0.1 K).

Zusammenfassung

Der globale Klimawandel muss in seinen Auswirkungen im Wesentlichen auf der regionalen und lokalen Ebene betrachtet werden. Folglich müssen Methoden des sogenannten 'Downscalings' entwickelt werden, um grob aufgelöste Ergebnisse globaler Klimasimulationen auf die benötigte hoch aufgelöste Skala in der Region von Interesse zu transformieren. Dies gilt besonders für Gebiete mit komplexen fein-skaligen Strukturen wie dem Untersuchungsgebiet der vorliegenden Studie, dem Einzugsgebiet der oberen Donau, das sich auf Süddeutschland und das westliche Österreich und somit auch bis in die Alpen hinein erstreckt. Hier müssen bodennahe meteorologische Felder auf einer extrem hohen Auflösung (1 km) für eine Reihe von Modellen der Klimafolgenforschung bereitgestellt werden.

Die vorliegende Studie konzentriert sich auf regionale Klimamodellierung (RCM), die sich des physikalisch basierten meteorologischen Modells MM5 bedient, um globale Klimasimulationen auf eine höhere Auflösung zu skalieren. MM5 wird auf einer Auflösung von 45 km über Westeuropa betrieben. In einem weiteren Skalierungsschritt werden die Simulationen des MM5 mittels eines statistischen Verfahrens auf die benötigte Auflösung (1 km) gebracht.

Verfügbare Studien zur regionalen Klimamodellierung lassen eine klare Trennung von Defiziten der globalen Modellierung gegenüber denen des regionalen Modells vermissen. Die vorliegende Arbeit bietet hierzu eine zweistufige Evaluierungsstudie (Schwerpunkt bzgl. Niederschlag) in alpinem Gelände. Im ersten Schritt wird MM5 mit beobachtungs-basierten Daten angetrieben (ERA40 Reanalyse). In einem Mini-Ensemble wird die optimale Konfiguration des MM5 ermittelt. Das Ensemble wird von drei verschiedenen Konvektionsparametrisierungen und zwei unterschiedlichen Formulierungen der horizontalen numerischen Diffusion aufgespannt. Es zeigt sich, dass der Einfluss (auf den simulierten Niederschlag) der unterschiedlichen Formulierungen der numerischen Diffusion ähnlich groß ausfällt wie die Abhängigkeit bezüglich der Konvektionsparametrisierung. Eine optimierte Referenz-Simulation (1991–2000) zeigt eine gute Übereinstimmung mit beobachteten Niederschlägen. Auch bodennahe Temperatur und Feuchte stimmen gut mit Stationsdaten im Alpenvorland überein, mit geringfügigen Abweichungen vorwiegend am Nachmittag, die jedoch häufig bei regionalen Modellen zu verzeichnen sind. Im zweiten Schritt werden zwei Langzeitsimulationen (1971–2000), angetrieben von beobachtungsbasierten Daten bzw. von einer globalen Klimasimulation (ECHAM5), gegenübergestellt. Der ECHAM5-Antrieb führt zu einer deutlichen Überschätzung des Niederschlags um bis zu 80 % in der kalten Jahreszeit, insbesondere im alpinen Bereich. Die großskaligen Strömungsverhältnisse der globalen Datensätze weisen für ECHAM5 gegenüber ERA40 vermehrte Tiefdrucksysteme auf, die vom Atlantik in den Alpenraum ziehen. Die Analyse 3-stündlicher Winddaten in den Zentralalpen, auf einem Niveau von 700 hPa, gemäß Geschwindigkeit und Richtung zeigen eine deutliche Verschiebung hin zu stärkeren westlichen und nord-

westlichen Winden. Dementsprechend aggregierte 3-stündliche Niederschlagsmengen fallen aufgrund übermässig verstärkter westlicher Winde erheblich höher aus.

Um diese vom antreibenden Globalmodell verursachten Unzulänglichkeiten des simulierten Niederschlags auszugleichen, wird eine klimatologisch basierte Korrektur auf die MM5-Ergebnisse angewendet. Diese Korrektur ist in den nachgeschalteten statistischen Skalierungsalgorithmus eingebettet. Die gesamte meteorologische Modellierung (globales und regionales Modell + statistisches 'Downscaling') wird aus Sicht der nachfolgenden hydrologischen Modellierung evaluiert. Hier erweist sich unter ECHAM5 die klimatologisch basierte Korrektur der MM5-Ergebnisse als unabdingbar für realitätsnahe Simulationen des mittleren monatlichen Abflusses und der täglichen Abflussspektren im Einzugsgebiet der oberen Donau. Ohne diese Korrektur führt der übermässige Niederschlag der kalten Jahreszeit zu einer massiven Überschätzung des entsprechenden Abflusses.

Mittels des zwei-stufigen Skalierungsansatzes wird beispielhaft ein globales A1B Szenario des IPCC für das 21. Jahrhundert (simuliert mit ECHAM5) für die benötigte Auflösung (1 km) im Untersuchungsgebiet aufbereitet. Zum Vergleich werden auch entsprechend behandelte Ergebnisse eines weiteren regionalen Klimamodells (REMO) betrachtet. Beide skalierten Datensätze stimmen in einem allgemeinen Anstieg der bodennahen Temperatur überein, mit einer besonders bemerkenswerten Erwärmung im Winter von bis zu 5–7 K gegen Ende des Jahrhunderts. Vergleichsweise höhere Zunahmen sind in den höheren Lagen zu verzeichnen. Für den Niederschlag stellt sich die Situation deutlich komplexer dar. Zumindest bezüglich einer substantiellen Abnahme im Sommer um etwa 30 % im Langzeittrend über das ganze Jahrhundert sind sich die Modelle einig.

Ein weiterer Schwerpunkt der vorliegenden Arbeit liegt auf der interaktiven zweiwege-Kopplung des MM5 mit einem hochaufgelösten (1 km) Landoberflächen/Vegetations/Hydrologie-Modell, um Nutzen hinsichtlich der meteorologischen Modellierung u.a. aus dessen hochentwickelten Formulierungen des Transports von Wasser im Boden und den sehr detaillierten Algorithmen der Evaporation von Pflanzen zu ziehen. Des weiteren verfügt dieses Modell über sehr differenzierte, hoch aufgelöste Klassifikationen der Boden- und Landnutzungstypen. Mit diesem neu geschaffenen Modellverbund konnten sehr realitätsnahe Ergebnisse bzgl. Niederschlag und bodennaher Temperatur im Einzugsgebiet der Donau erzielt werden (Simulationszeitraum 1996–1999). Die Überschätzung des mittleren jährlichen Niederschlags konnte auf 5 % reduziert werden, gegenüber 13 % mit dem Standard-MM5. Die Unterschätzung der mittleren jährlichen bodennahen Temperatur von 0,9 K konnte fast vollständig ausgeglichen werden (0,1 K).

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Chapter 1

Introduction

1.1 Scientific problem—global climate and its change

Global climate and its change today is a universal concern. It is a subject of sometimes vigorous discussions, not only in the scientific but also more and more (over the last two decades) in the general community. A first systematic attempt to quantify the underlying effect of carbondioxide acting as a greenhouse gas interfering with the atmosphere's radiation budget was performed more than a hundred years ago by Arrhenius (1896). This first estimate resulted in an increase of global mean temperature by 5–6 Kelvin for a doubled (pre-industrial) atmospheric concentration of CO_2—falling almost surprisingly well in the range given by modern, substantially more complex approaches.

Arrhenius speculated on the positive effects of global warming such as enhanced crops, estimating, however, a time of 3000 years necessary for the doubling of the carbondioxide content in the atmosphere, mainly due to burning of fossil fuels. Actual figures today rather suggest a time scale of merely about a hundred years. Furthermore, industrialization and intensified farming affects a whole set of greenhouse gases, beyond carbondioxode, from methan to artificial substances such as CFCs, each with dramatically increasing concentrations. Thus, global climate most probably will change much more rapidly than foreseen by Arrhenius. Positive effects, that potentially would have been brought about by a slowly warming climate, thus probably will be outweighed by a complex variety of negative impacts caused by the rapid change of man's natural environment. The sheer speed of this change may cause an urgent need for massive adaptation efforts at least in some regions of the world. There still might be some 'winner' regions but it will be hard if not impossible to devise any kind of fair international mechanisms of compensation for the climate change 'losers'. Additionally, the increase of worldwide population in the last century on the one hand aggravates (regional) vulnerability to climate change and on the other hand further boosts emissions of greenhouse gases.

The enormous complexity of the climate system together with the manifold aspects of climate change impacts—positive as well as negative—on the natural conditions of living called for more elaborate and precise, ideally physically based instruments to mathematically reproduce the relevant processes and to project the possible future developments. Consequently, so-called general or global circulation models (GCMs), describing the basic (thermo-)dynamics of the Earth's atmosphere driven by incoming solar radiation, were firstly developed in the 1950s (Phillips 1956). General circulation models first of all were related to numerical weather forecasting (Charney et al. 1950). To serve for climate research purposes as fully-fledged global climate models they had to be complemented considerably with additional routines describing climate relevant processes, connected for example to the oceans as well as the landsurface and its vegetation. These routines have to capture realistically the corresponding mass (e.g. water, carbon) and energy budgets, allowing also for a variety of feedback effects. More and more processes were identified as 'climate-active', such as the complex interplay of chemistry and global transport of stratospheric ozone. Constant improvements in computer technology made over the last decades following Moore's Law (1965), who predicted a doubling of hardware capacity roughly every one or two years, came just in time to keep up with the increasing demands of numerical atmospheric simulations.

In the meantime substantial progress has been made in model development. McGuffie and Henderson-Sellers (2001) give a quite comprehensive overview of the first 40 years of numerical climate modelling. They also summarize some relevant studies giving confidence that the recent global warming in the twentieth century cannot be explained solely by natural forcings but is only explicable if anthropogenic greenhouse gas emissions are also taken into account in simulations of the global climate system.

Modern state of the art global climate models are characterized by a remarkable degree of accuracy and reliability, given the enormous complexity of the climate system. They are capable to realistically reproduce many features of global present day (i.e. the last 150 years) climate conditions as is continuously monitored by projects such as the 'coupled model intercomparison project' (CMIP, Covey et al. 2003) that entered its fifth phase in 2010. Covey et al. (2003) analyzed simulations from 18 coupled global atmosphere–ocean general circulation models (AOGCMs). The models reveal relative best performance in the simulation of large scale patterns of mean annual surface air temperature, with a model mean differing from observations less than 2 K (apart from the polar regions). Simulation of precipitation is much more difficult, as reflected by comparatively large intermodel standard deviations. This had to be expected as the generation of precipitation is a complex process that is highly influenced by regional and local forcings that might not be captured properly by the global simulation models. Hence, different approaches in corresponding physics routines and different parameterizations used in the models can lead to substantial discprepancies. Furthermore, quantitative observation of precipitation is particularly difficult making validation generally a delicate challenge. Error statistics of the multi-model analyses in terms of total spatial and temporal variability of surface air temperature, sea level pressure and precipitation fall into the range of correspondingly analyzed observational uncertanties. Thus, Covey et al. (2003) also raise the very basic and general issue of at least partially scarce or questionable observational data.

Based on the additional knowlegde gained from such extensive modelling studies a whole set of GCMs were upgraded and/or redesigned substantially (e.g. Collins et al. 2006, Delworth et al. 2006, Johns et al. 2006). The substantial improvements made even put within reach realistic simulations of specific complex features, such as El Niño and monsoon or the North Atlantic Oscillation, some of which are based on intricate teleconnections between troposphere, stratosphere and the oceans. These phenomena are characterized with variabilities on different typical time-scales from seasons to decades, the correct simulations of which are important to further corroborate confidence in the reliability of AOGCMs.

Still, projections of future climate naturally are not free of uncertainties and imponderabilities. Clouds and their impact on climate, for example, are not yet fully reproduced by GCMs. Their direct net effect is, on the one hand, made up of cooling of Earth's surface due to the reflection of solar radiation back into space. On the other hand they are responsible for additional warming due to longwave emissions towards the surface that amongst other factors is strongly governed by cloud temperature (i.e. essentially by cloud height) and thus by vertical profiles of temperature and moisture (Soden 2006). Furthermore, via deep moist convection they are involved in the overturning of considerable amounts of air masses and energy. Another source of non-negligible uncertainties are aerosols, that have many different sources and accordingly exist in a great variety of substances, sizes, and forms, correspondingly exhibiting manifold physical and chemical properties (such as hydrophilic/-phobic, refractive index, etc.). Thus, they interfere directly as well as indirectly with various atmospheric variables. In particular, they play also an important role as condensation nuclei in cloud formation and hence, amongst others, for cloud optical properties (Twomey 1974). The net effect of aerosols on climate change hence is still a subject of ongoing research. An elaborate study on this issue, combining labaratory data and field campaigns on aerosol nucleation from the gas phase and AOGCM simulations, was, for example, performed by Kazil et al. (2010) using an AOGCM that is equipped with a sophisticated microphysical aerosol module.

The overall results of GCM simulations for the twentyfirst century embedded in global socio-economic scenarios, prescribing different pathways of future emissions of climate-active substances, nevertheless today reached a level of maturity, such that they cannot be simply ignored. They rather already give a reasonable basis for serious land mark decisions of global climate policy. Effectively, the work on global climate research is done in a multi-model ensemble approach, with research groups all over the globe participating in a joint effort to gain as much essential insight into the climate system and its future behaviour as possible. One of the main challenges of the Intergovernmental Panel on Climate Change (IPCC, founded 1988) accordingly is to review and assess all relevant research contributed by scientists all over the world and to critically prepare and process the results and their uncertainties for policy makers. To increase general awareness of politicians and societies for climate change issues and for any kind of adaptation strategies a regionally differentiated view on possible ramifications of climate change is indispensible and has to be provided by the research community.

1.2 The regional scale—the GLOWA-Danube project

The increasing interest in regional climate studies is reflected again in the latest IPCC report (2007), where the impacts of climate change are not assessed on the global scale but effectively for various regions of the globe. Thus, as long as global climate models are too coarse in their horizontal resolution ($>$ 100-200 km) to give a comprehensive and detailed picture of the manifestation of global climate change on a regional or even local scale—where the human society finally has to face this change—further processing, i.e. downscaling of AOGCM output will be indispensable. The IPCC defines 'downscaling' in very general terms as 'generating information below the grid scale of AOGCMs' (Christensen et al. 2007b)

The most important meteorological variables for a prospering natural environment and thus for human living are precipitation and near surface temperature on the regional and local scale. Even seemingly moderate changes of these variables might bring about substantial consequences for the affected regions and societies. Accordingly a number of studies have been initiated by policy makers to get a scientific basis for their decisions on, e.g., investments in climate sensitive infrastructure or long term legislation for agriculture. Recent projects extend their investigations from purely natural towards socio-economic sciences, such as the GLOWA-Danube project (Ludwig et al. 2003), in the framework of which the present study was initiated. The present dissertation accordingly describes work that was carried out as part of this project. GLOWA-Danube is embedded in the GLOWA program of the German Federal Ministry of Education and Research (BMBF) as part of its initiative on research for sustainability. Its subject is medium and long-term availability of water exemplified for a handful of river catchment areas, each of which investigated by a corresponding interdisciplinary cluster project. Three of these catchments are located in North and West Africa (rivers Drâa, Ouémé, Volta), one in the Middle East (Jordan). In Germany along with the upper Danube catchment also the catchment of the Elbe river has been assigned as an area of considerable interest. The aim of GLOWA-Danube thus is to investigate various aspects of the regional water cycle relevant for a sustainable use of water, not only but primarily under the conditions of a changing climate. GLOWA-Danube has its focus on the upper Danube catchment mainly located in the southern part of Germany and western Austria and thus extending into the European Alps. The upper Danube catchment covers 77,000 km^2 and is a densely populated area with more than 10 million inhabitants. Major parts of it are intensively used by agriculture and furthermore it is highly industrialized. Especially for such areas, characterized by a high variability of various parameters, downscaling has to bridge the gap between GCMs and the regional and local scale, capturing consistently the finer details of e.g. orography and landuse. This is necessary in order to give reliable results for the projection of regional climate and therefore eventually for the development of proper mitigation and adaptation strategies.

Within GLOWA-Danube global climate simulations for present day conditions as well as encompassing the whole 21st century had to be downscaled for the region of interest to provide the required meteorological input data on the suitable, very high resolution of 1 km for the subsequent impact models. The present study essentially was set up to accomplish this goal.

1.3 Downscaling of global climate simulations: methods

A meteorological model is by principle not able to reproduce meteorological features on a scale that is finer than its horizontal resolution. The model is not directly provided with the corresponding fine scale forcing, and even if some parameterizations of a model incorporate subgrid scale information, such as grid box variability of terrain height, the simulation will again only give a response on its effective resolution. Hence, further downscaling of GCM results is necessary to reach the target resolution, required by subsequent impact models.

Several techniques for downscaling have been proposed and applied over the last two decades. Wilby and Wigley (1997) give an overview of downscaling techniques, divided into four different basic classes: regression methods, weather pattern approaches, stochastic weather generators and so-called limited area models. Fowler et al. (2007) follow these definitions in their extensive review on the performance of the different downscaling approaches in the view of hydrological modelling. Regression methods rely on linear or non-linear relationships between the subgrid-scale parameters (the predictands) and resolved scale GCM-generated variables (the predictors). A typical predictand-predictor set would be precipitation and surface layer pressure or geopotential height (e.g. Zorita and von Storch 1999). Also combinations of several predictors are possible. Widman et al. (2003) find a good performance of precipitation itself, simulated by a GCM, as predictor for downscaling precipitation to the regional scale. This, however, requires already a realistically simulated large scale rain. A prerequisite for a weather pattern approach is a systematic classification of typical large scale atmospheric (circulation) patterns as subjectively pooled, for example, to a catalogue of European 'Großwetterlagen' by Gerstengarbe et al. (1999). These patterns are statistically related to observed values of the desired meteorological variable to give probability distribution functions that can be applied to downscale corresponding GCM generated sequences of synoptic situations. Enke et al. (2005) accordingly designed an objective classification procedure for the application in downscaling and managed thereby to limit undesired within-class variability of associated regional climate parameters. Statistic weather generators (e.g. Watts 2004) are commonly based on first- und up to third-order Markov chains; they tend, however, to show deficiencies in building physically realistic and consistent data under changing climate conditions.

Statistical methods are quite inexpensive in terms of computational resources which can be a major practical advantage in many applications. They can even be applied for the evaluation of variables of interest that are not provided by a regional model (Christensen et al. 2007b). The availability of long and comprehensive observational data records, however, is essential for the training or calibration of the statistical models—this prerequisite can not be fulfilled at all for many regions of the globe. Furthermore, fixed statistical dependencies implicitly presume a stationarity in statistics as e.g. in the derived predictor-predictant functions that in general might not hold true in an altered climate. Hewitson and Crane (2006), who perform a comparison study of empirical/statistical and dynamical downscaling, raise some concerns that the immanent stationarity of statistical methods, trained under present day climate conditions, might be prone to systematically underestimate future climate change, that falls outside the variability of data observed so far. Fixed statistics also might lead to underestimated temporal (day-to-day as well as interannual) variability in the projected regional climate if this variability is not already present in the GCM simulation. Evaluation of statistical methods based on separate observational periods, that could represent different regimes of global climate, remains questionable in the view of future climate changes, that are (presumably) larger than changes observed in the past.

Only so-called 'dynamical' downscaling via a limited area model or rather a 'regional climate model' (RCM) nested into the simulation of a GCM is in principle fully capable of conforming to altered statistical relationships between the large scale and the regional and local meteorology—essentially by not relying on past statistical relationships (at least as much as possible) but by obeying principally only to basic laws of physics. It has to be mentioned, though, that parameterization schemes of RCMs have been developed and validated under present day climate conditions. Thus it can not be ruled out a priori that under a changing climate they might fall somewhat out of their optimal range of operation.

As a further advantage of RCMs they also inherently provide a complete set of fully consistent meteorological fields, what cannot be guaranteed for a priori by some statistical approaches (Christensen et al. 2007b). Beyond enhanced spatial variability RCMs also can infer additional temporal variability to various meteorological fields by incorporating regional and local responses into the downscaling process. Schmidli et al. (2007), for example, find statistical approaches to strongly underestimate interannual variations of downscaled precipitation compared to RCMs. Salathé et al. (2007) compare different downscaling approaches applied in the area of the United States pacific northwest. They find statistical methods valuable tools that, however, lack the ability to capture important mesoscale responses to global climate change such as changes in the surface radiation budget due to altered cloudiness and snow cover locally adding to the overall (global) warming. Furthermore, the forcing exerted onto the regional climate by global circulation changes can be complemented in RCMs, e.g., by the regional forcing of (man made) land use changes for certain scenario experiments (Paeth 2007).

Last but not least, only RCMs can conform to the increasingly relevant request of studies on regional climate, such as GLOWA-Danube, to capture a fully, two-way interactive feedback of the underlying surface, including a truly interactively responding vegetation, onto the regional and local meteorological variables. Hewitson and Crane (2006) expect this feedback to be relevant for climate projections, the relative impact of which, however, still representing an 'element of uncertainty'. An indispensible prerequisite for a bilateral coupling approach naturally consists of a thorough validation of the atmospheric as well as the landsurface/vegetation model part in a stand alone mode to prove the respective reliability and skill in the realistic simulation of key variables to be exchanged in the coupling process. Two-way coupling makes it even more important to choose the appropriate physics packages and parameterizations to ensure the best possible model performance. Otherwise the overall model will most likely produce highly unrealistic results with a considerable tendency for drifts or even towards numerical instability.

The computational demand of RCMs, on the other hand, is quite substantial. The progress in computer technology over the last 20 years, however, meanwhile allows also for extensive studies (some of which even reaching horizontal resolutions of down to 10 km) relying on multi-decadal regional simulations with costs that are well justifiable in the view of the aforementioned advantages and benefits of this technique.

In addition to these single downscaling classes also combinations of several approaches are feasible. For so-called statistical-dynamical downscaling (Fuentes and Heimann 2000), for example, RCM simulations are only performed for a set of classified large-scale weather situations, prevalent for the region of interest as observed or given by a GCM. The actual climate conditions on the regional scale are then derived by weighting the results according to the recurrence of the specific weather types in GCM scenarios for the future. This significantly reduces the computational costs compared to the plain RCM approach. The whole variability of regional climate, however, can not be reflected by this method.

Against the background of the various pros and cons of empirical/statistical and dynamical downscaling, as discussed above, a somewhat pragmatic division of tasks has been proposed by Hewitson and Crane (2006). They suggest that empirical techniques are appropriate to give a 'first-order response' on the regional scale to global climate change. Due to their cost-effectiveness they allow for a comparatively quick and inexpensive assessment of regional impacts of a whole set of various global scenarios and simulations, respectively. RCMs, on the other hand, are thus to be used as higher order methods to (at least in principle) incorporate further relevant processes into the downscaling of a specific subset of the statistically pre-evaluated global simulation data, possibly revealing additional details of the resulting regional climate.

It is not the purpose of the present study to give an assessment of the relative reliability and robustness of statistical versus dynamical downscaling techniques. Both approaches in general have been evaluated successfully showing suitable performance and skills. Reasonable arguments, depending to some extent on the specific study, have been brought forward by various researchers for both methodologies. The target-resolution of 1 km required by the downstream impact models in the GLOWA-Danube project would not have been feasible with dynamical downscaling alone. Thus, in the course of this thesis as a new approach a combination of RCM simulations and a subsequent statistical downscaling will be discussed. A pragmatic compromise or synthesis will be presented, eventually combining the advantages of both techniques and attenuating the shortcomings of the respective 'stand alone' approach. The regional model here will be operated on a moderate horizontal resolution in order to limit the computational demand. The further processing to the desired fine-scale resolution will then be accomplished by a very cost-effective climatology-based statistical approach that can be applied 'online' during the simulation. This will eventually also allow for long-time simulations in a fully coupled interactive mode between a regional model and a sophisticated high-resolution landsurface/vegetation/hydrology module—a prerequisite and aim of the overall study setting the framework of the present work.

The main focus of the present study is on the performance of a regional climate model that will be scrutinized first of all with respect to simulated precipitation as this is the most dominant variable for a hydrological project such as GLOWA-Danube. Furthermore, also simulated near surface temperature will be analyzed. Accordingly an overview of the current state in regional climate modelling will be given in the following section.

1.4 State of the art in regional climate modelling

First studies of regional climate modelling came up around 1990 and only comprised several weeks or at most a few years of simulation time. They were merely able to give more than a general proof of concept due to the limitations of computer resources at that time.

For example, Giorgi (1991) carried out a simulation for July 1979 testing different physics parameterizations for the mountainous western United States. He addressed some intrinsic problems of a regional model that was not yet properly adapted to its new purpose of working in so-called climate mode. In particular, the importance of a sophisticated landsurface and vegetation scheme for long term climate-mode runs was emphasized. A specific model deficiency was suspected by Giorgi to lie in the horizontal numerical diffusion computed along the terrain following sigma surfaces, which was not further addressed there but will be discussed later here in this study. Bates et al. (1995) were able to reproduce in a two-year simulation at a horizontal grid resolution of 60 km the regional meteorological cycle for the Great Lakes Region which would not have been possible at all at the coarse resolution provided by a global model at that time.

The general concept of regional climate modelling naturally was, once established, applied to various regions of the world and to specific meteorological phenomena. Liu et al. (1994), for example, managed to reproduce the general features of the the Monsoon over East India concerning circulation, precipitation and land-surface temperature. Bhaskaran et al. (1996) also conducted a set of seasonal simulations of the Indian summer monsoon using a 50-km RCM. They emphasize that a necessary prerequisite for RCM studies is a large-scale climatology from the driving GCM that is realistic over the region of interest.

Jacob et al. (1997) designed a regional model named REMO and applied it to both the Baltic Sea and the Indian Monsoon. They also emphasize the need for realistic boundary conditions whose relative impact (compared to e.g. the specific choice in their set of implemented model physics) seemed to be dominant. Giorgi et al. (1998) found significantly improved precipitation patterns simulated with their regional model called RegCM for the Central Plains of the U.S. due to a strongly improved quality of the driving GCM compared to an earlier experiment. Christensen et al. (1998) showed in a 9-yr-long simulation at 57 km resolution that a regional model substantially improves the representation of the hydrological cycle compared to a coarse resolution GCM alone. However, they also stress that the regional model inevitably inherits systematic errors from the global model. Hence for the purpose of validation a regional model should be driven by high-quality global numerical weather prediction (NWP) analyses rather than by GCM output. As summarized by Giorgi and Mearns (1999), a useful separation of model-internal errors from errors imposed from the driving model is otherwise very difficult.

Up to the late 1990s the validation of the nesting approach on climatological time scales suffered not only from insufficient computing resources but also from the lack of high quality, consistent long time data sets of observed global meteorology that could serve as appropriate large scale input to RCMs. This was overcome by major endeavours by NCEP/NCAR (National Centers for Environmental Prediction, National Center for Atmospheric Research, USA) and the ECMWF (European Centre for Medium-Range Weather Forecasts) who accomplished about 40-year long records of consistent global analyses of atmospheric fields by compiling all available observational data and processing them by means of a frozen state-of-the-art global data assimilation system (Kalnay et al. 1996, Uppala et al. 2005). Pan et al. (2001) conducted simulations with two regional models for the central United States at a resolution of about 50 km driven by NCEP reanalysis data for the years of 1979 to 1988. They compared these results regarding precipitation patterns to simulations that used a 10-year window from a GCM run roughly representative to 1990 as boundary conditions. The bias of the RCM simulations driven by reanalysis data was, naturally, generally lowest. Kunkel et al. (2002) further analyzed this 10-year simulation and obtained some encouraging results concerning heavy precipitation statistics. Deficiencies are ascribed to the location of some boundaries close to data-poor oceanic regions and to the parameterization of convection. Duffy et al. (2006) collated several GCM/RCM studies for present and future climate that, however, are not complemented by reanalysis driven regional climate simulations. So they merely could give an estimate of uncertanties for the particular model combination as a whole.

During the last decade, there were also a number of studies considering the region of the Upper Danube catchment. In the framework of BayFORKLIM (1999) Grell et al. (2000) did some pioneering work in regional climate modelling with a set of up to 5-year-long high resolution (60, 15 and 1km, i.e. cloud resolving) GCM-driven simulations for the European region comprising Bavaria. Focusing on simulated precipitation in complex terrain for parts of the European Alps they identified resolution dependent up- and downstream effects on generated precipitation in their model configuration. Within the MERCURE project, Hagemann et al. (2001) were able to improve simulated precipitation amounts and 2-m temperature particularly for the less mountainous parts of the Danube catchment by improved land surface parameters. They also pointed out that verifying simulated rainfall in mountainous regions suffers from substantial observational uncertainty. An intercomparison study by Hagemann et al. (2004), including the Danube catchment (as one of several target areas), addresses the 'summer drying problem' (i.e. dry and warm bias in summer) common to the four regional models investigated. A whole set of possible reasons from problems in model dynamics to deficiencies in several physics parameterizations was suggested but no conclusive explanation could be given by the authors.

As climate impact studies require not only a proper simulation of relative trends but of absolute values of the meteorological key-variables, it is of major importance to validate and further improve the capability of climate models to, first of all, quantitatively reproduce the present day climate. Thus, meanwhile extensive long-term (30 years and more) comparison studies have been performed evaluating whole sets of different state of the art models like e.g. in the PRUDENCE project (Jacob 2007). RCMs with horizontal resolutions mostly around 50 km but also, for some experiments, with up to 12 km were used. Ten regional models were evaluated mainly with respect to precipitation and near surface temperature for present day climate. Again, only the combination of a GCM and several RCMs has been tested, which in general does not unambiguously reveal where the actual problem lies: in the GCM or in the RCM. Additional RCM simulations driven by ERA40 reanalyses of ECMWF could have been highly informative.

A study by Suklitsch et al. (2008), in contrast, used ERA40 reanalyses to drive high-resolution (10 km) simulations with the regional model CCLM for the Alpine region. Here, quite a strong influence on model results of domain size and vertical resolution compared to the implementation of various parameterizations and numerics was found. Among other factors, the comparatively small domain size is suspected to be critical given the big scale-jump between driving fields and the regional model.

A very recent extensive intercomparison study for a set of high resolution (10 km)

RCMs driven with ERA40 data was conducted by Suklitsch et al. (2010) over the Alpine region with a total of 62 experiments limited to only one year of simulation time. They evaluated model performance in terms of 2m-temperature and precipitation for different subregions of their model domains finding no subregion that is captured best by all models in terms of both variables.

All in all substantial achievements in regional climate modelling over the last two decades have to be acknowledged. Quantitative simulation of precipitation, particularly in mountainous terrain, however, still remains an issue of concern. Subsequent impact models, on the other hand, depend essentially on realistic rainfall quantities. A project such as GLOWA-Danube, that is dedicated to the research on the water cycle and its future development, cannot succeed from the very outset without robust simulations of precipitation. The problems especially arise for convective situations in summer, that obviously often are not captured properly by the corresponding parameterization schemes. The substantial variety of approaches to tackle deep moist convection thus opens a wide field for further systematic investigations—and improvements to be achieved in the present study. Beyond that, also certain basic numerical formulations of the models, not directly related to rain generation, such as horizontal diffusion, will be regarded in the analysis here. Furthermore recent literature often lacks a clear separation in the investigation of deficiencies in RCM-simulated precipitation against errors already imposed by the driving GCM data. Such an unambiguous separation, however, is an essential prerequisite for any efforts for improvements.

1.5 Goals

The goals of the present dissertation comprise optimizing and performing long time RCM simulations (for present day conditions and for a future climate change scenario) and additional statistical downscaling to reach the very high horizontal resolution required particularly by the downstream hydrological model called PROMET that was provided by the hydrology group of GLOWA-Danube. Furthermore, the regional climate model MM5 had to be two-way coupled to PROMET, in order to benefit from its sophisticated formulation of processes associated with the underlying landsurface and vegetation, to allow for future studies capturing even more details, processes and feedbacks of the complex regional climate system.

For any climate change study, an essential prerequisite is well documented evidence that the model chain used is reasonably capable of simulating the observed present day climate within a narrow band of tolerable deviations. First and foremost, realistic quantitative simulation of precipitation is still one of the major challenges in climate modelling as well as numerical weather prediction, particularly in mountainous areas. On the other hand for climate change impact studies, such as in the field of hydrology, quantitatively robust simulation results of precipitation are indispensable as input to the 'downstream'-models.

The corresponding goals of this work are each outlined in the following.

1.5.1 Identification and validation of the appropriate configuration of MM5, driven by ERA40 reanalysis data

The technique of nesting a regional climate model into a global model requires a quality assurance in two steps. First the regional model's ability to capture the meteorology in the area of interest has to be scrutinzed by simulations driven by 'optimal' observation-based meteorological input fields. Should the regional simulations reveal noticeable deficiencies appropriate measures for improvements, i.e. adjustments of the code, have to be implemented where applicable and possible.

In the sense of a stepwise validation of regional climate simulations the first aim of this work is to assess the performance of a regional model, namely MM5, driven with ECWMF's ERA40 data, to realistically simulate first of all precipitation and secondly near surface temperature of the present day climate in a recent decade, i.e. the 1990s. In the course of this validation advantage will be taken from the variety of parameterizations and physics options offered by the MM5 modelling system—MM5 thus presents itself as an ideal and robust 'testbed' for the investigation of various processes and simulation approaches. The generation of precipitation is not the least governed directly and predominantly by the convection parameterization. Accordingly a set of sensitivity experiments for four selected years, typical of the 1990s in terms of precipitation, comparing three different widely used cumulus convection schemes will be scrutinized. This will be set in context to the possible side effects of numerical diffusion already suspected by Giorgi (1991). This dissertation thus addresses a long-standing but barely, if at all, investigated problem of meteorological modelling by comparing simulations using the common method of computing numerical diffusion along the terrain-following coordinate surfaces with simulations using the truly horizontal formulation implemented in MM5 by Zängl (2002). According to the goals of GLOWA-Danube, the focus is set on the German and Austrian parts of the Alps, using operational observations of the German and the Austrian weather services for validation. As a result the optimal configuration of MM5 for the research area will be identified. Furthermore, a detailed verification of simulated precipitation and near surface temperature for a corresponding reference simulation covering the whole decade of the years of 1991 to 2000 will be presented.

A fundamental issue in this context, that will be shed some light on in the course of the present work, concerns the observational data building the basis of the validation efforts. Not only data availability but also representativity of measurements especially for precipitation in mountainous terrain, poses a widely unsolved problem. What is the exact 'observational truth' against the background of which a fair validation can be performed? What would be a fair, straightforward and comprehensible assessment of RCM results? Therefore, in the context of this first validation step also the issue of the observational basis and some basic, straightforward error measures will be discussed.

The ERA40 reanalysis here presents itself as an invaluable source for the necessary boundary data to drive the regional simulations of this work. Over Europe the ERA40 dataset compares reasonably to the NCEP/NCAR reanalysis as has been investigated by Greatbatch and Rong (2006). They found, however, some discrepancies mainly over Northern Africa and Asia for the northern summer hemisphere. Wang et al. (2006) analyzed both data sets with respect to extratropical cyclone activity with best correspondence again over the European area. In their view ERA40 in general is superior due to its higher resolution, updated data assimilation system, and more/improved observation data assimilated.

1.5.2 Analysis of MM5 simulations driven with AOGCM (ECHAM5) output

The next main goal of this thesis consists in the second necessary step of validation, i.e. monitoring the performance of the nested model approach after switching from 'observational' input fields to the output of a state of the art global climate model for the same period in time. This step-by-step approach should help to systematically relate any errors either to the GCM or the RCM. To complement recent research, which focussed predominantly either on GCM-output or reanalysis data as input to RCMs, a direct and coherent comparison study between reanalysis- and GCM-driven RCM simulations will be presented. Particularly in mountainous terrain the transition from observation-based to GCM input data might reveal essential deficits in the overall simulation even for a 'perfect' RCM. Here seemingly minor differences between the observed and GCM-generated large scale climatologies could entail substantial deficiencies in sensitive variables and thus first of all in precipitation. These effects do not appear to have been investigated systematically so far in the existing literature. For this study ERA40 re-analysis data will be replaced by GCM simulation results as input to MM5. The GCM used for the present study is the ECHAM5 model developed at the Max Planck Institute for Meteorology, which is based on the ECMWF's general circulation model (Roeckner et al. 2003). The ECHAM model 'family' has a long record of contributing to the scientific basis of the IPCC with long-time climate simulations. Results of the former versions 3 and 4 have been considered in IPCC's third assessment report (IPCC 2001), whereas ECHAM5 simulations are evaluated in the latest, i.e. the fourth assessment report (IPCC 2007), comparing well with other state of the art AOGCMs.

Roeckner et al. (2006b) give an elaborate insight in the dependency of ECHAM5's simulated climate to the resolution in the horizontal as well as in the vertical—not the least the simulated large scale flow shows substantial sensitivity to the various combinations. Focussing on storm tracks, Bengtsson et al. (2006) find general good agreement on the whole northern hemisphere between long-term simulations, with a resolution of T63L31 (i.e. a horizontal spectral resolution according to truncation for wavenumber 63 and 31 vertical layers), and corresponding ERA40 data. Yet they still mention larger differences for smaller regions which might be relevant in the view of the present work.

1.5.3 Statistical downscaling of MM5 output and validation of the overall meteorological simulation approach in view of downstream hydrological simulations

The target grid size that was agreed upon within the overall GLOWA-Danube project is 1 km. As has been discussed above regional climate modelling cannot provide long-time climate simulations, covering at least several decades, with reasonable resources of CPU- as well as wall clock time at this high horizontal resolution. Thus, an additional subsequent statistically based downscaling procedure had to be devised, refined (compared to an earlier stage) in the course of the present study, and applied to the regional climate simulations. This eventually will yield the meteorological input to downstream impact models on the joint fine-scale mesh as it has been implemented in the overall modelling framework of GLOWA-Danube.

This combined approach thus will reconcile dynamical and statistical downscaling, preserving the respective advantages of both techniques for the use in climate change impact research. On the one hand it will ensure a consistent physically based linkage to global climate models via a RCM that performs the first downscaling step. On the other hand, it will limit computational costs using also a very cost-effective statistical approach for the subsequent second step.

In case that the meteorological model chain, i.e. the combination of global and regional model, exhibits appreciable biases that can not (or rather 'not yet') be corrected for by properly adapting the respective formulations or parameterizations in the model code, also a systematic bias correction has to be applied to the model results as a working solution for overall regional climate impact studies. Consequently, the downscaling algorithm presented in this study also has to be capable of correcting for discrepancies identified with the help of the intercomparison of present day simulated and observed climatologies.

The algorithm presented is designed such as to perform the fine-grid downscaling together with the bias correction 'at one swoop', saving valuable computing resources and thus allowing for its 'online-' implementation into the overall GLOWA-Danube simulations.

The combined downscaling approach and particularly the bias correction has to be assessed in its performance in the view of downstream impact modelling. Hydrological modelling, the key issue of GLOWA-Danube, is most suitable in this sense as it gives an integrated, very sensitive response to the interplay of various meteorological fields. Any systematic discrepancies or inconsistencies in the meteorological model chain will be revealed by the comparison of observed and simulated catchment discharge data. Particularly evaluations for observed global climatologies versus AOGCM output, used as the primary input to the overall simulations, will give valuable insights. This eventually should serve to substantiate the achievement of goal number three, i.e. the successful implementation and validation of the overall meterological simulation and downscaling approach (dynamically plus statistically based) with respect to its subsequent application in the field of hydrology.

1.5.4 Performing and analysing a regional climate change scenario in the upper Danube catchment

GLOWA-Danube depends on reliable, high-resolution regional climate change scenarios for the 21st century in the area of the upper Danube catchment. Using the dynamical-statistical downscaling approach, refined and analyzed based on the achievements of the first three goals of this study, the fourth goal is to accordingly further process a global climate change scenario, as conceived by the IPCC and simulated with an AOGCM. Due to the overall limits of computational resources in GLOWA-Danube, not only with regard to meteorological modelling but also due to substantial simulation requirements of other disciplines such as plant ecology and hydrology, the project had to confine itself to one single scenario. Accordingly the somewhat moderate so-called A1B-scenario was selected. Consistently with the evaluation process of this study a global dataset as simulated with the ECHAM5 model (in an identical configuration as that used for the present day control run) serves as input to MM5.

The evaluation of the regional scenario focusses on the key parameters precipitation and near surface temperature. One purpose of this analysis also is to raise some awareness of the need for a careful evaluation of climate change scenarios and the possible ambiguities brought about by different analysis approaches or 'views' on simulation results.

1.5.5 Interactive coupling of MM5 to a high resolution landsurface-vegetation scheme

Last but not least, neither from the scientific nor from the technical point of view, a further major task and challenge of this dissertation is the endeavour to achieve the fully interactive coupling between the regional climate model MM5 to the advanced high-resolution landsurface-vegetation-hydrology model PROMET. This model is provided by the hydrology group participating in GLOWA-Danube and offers, for example, enhanced algorithms for inner-soil transport of moisture as well as more detailed descriptions of evapotranspiration by different plants. Moreover, it relies on a much more differentiated classification of soil- and landuse-types compared to the MM5 landsurface scheme. The new model composite has to be validated on the basis of a testsimulation comprising a set of several annual cycles. It then will be ready to be implemented into the overall joint model DANUBIA that had to be devised and constructed within the GLOWA-Danube project. Thus, one of the primary objectives of GLOWA-Danube, i.e. to establish a simulation platform with contributions of all relevant, participating disciplines, will be fulfilled on the part of regional climate modelling. This eventually will give a basis for future all-embracing research on a whole variety of aspects concerning the development of the regional water cycle under changing global climate conditions.

The present study is organized as follows. Chapter 2 of this dissertation gives a short overview of the main technical characteristics of the ERA40 reanalysis, the ECHAM5 model, and the regional model MM5. The experimental setup, including more detail on the relevant code of MM5, is given in chapter 3, where also the observational basis is explained. The results of the first validation step, i.e. the performance of MM5 driven by the 'observational' ERA40 data and its sensitivity to various convection parameterizations and formulations of the horizontal numerical diffusion is discussed in the first section of chapter 4. The second section presents results for the identified optimal reference configuration of MM5 for the whole decade of the years 1991 to 2000 and extends the analysis to near surface temperature and moisture. The consequences of switching the driving data set of MM5 from ERA40 to ECHAM5 for the years of 1971 to 2000 (i.e. the second step in the validation of the dynamical downscaling approach) are presented in chapter 5, particularly by analyzing the results of simulated precipitation of the regional simulation against the background of the large scale flow. Chapter 6 illustrates the pragmatic statistical downscaling approach, including a bias correction, developed to further process the RCM output to a horizontal resolution of 1 km required by the subsequent hydrology model, the results of which (simulated in a 1-way coupled mode) are presented in the last section of this chapter. The regional characteristics of the specific A1B global climate change scenario, as gathered for the upper Danube catchment by the overall downscaling (dynamical plus statistical) approach, are analyzed in chapter 7. Chapter 8 is dedicated to the interactive coupling of MM5 to the landsurface-vegetation-hydrology model PROMET and the analysis of this new model composite. Chapter 9 summarizes and concludes this study and gives some suggestions for promising future work.

Chapter 2

Climate models and datasets

The evolution and state of the art in (regional) climate modelling was already outlined in the introduction of the present work. This chapter gives a brief overview of the basic technical features of the complex meteorological models relevant for this study. These models are the global climate model ECHAM5 (Roeckner et al. 2003), the regional model MM5 (Grell 1994), and furthermore ECMWF's global data assimilation system, that was used to establish a global 40-year long continuous and consistent three-dimensional observation based set of meteorological data, the ERA40 re-analysis (Uppala et al. 2005). After some introductory remarks on characteristics common to these models (and a whole set of similar models), the following sections will give some respective details.

Numerical, physically based models are technical tools to represent and reproduce the governing processes in the atmosphere (Trenberth 1992, Warner 2011). They help to gain a deeper understanding of each single process and its intrinsic time and spatial scales, and moreover of the complex interplay of these processes altogether. Based on this advanced understanding of nature the models itself in turn can be improved and completed allowing for increasingly realistic simulations of the natural atmospheric conditions. Comparing results of different models also stimulates further model improvements (e.g. Covey et al. 2003). Eventually, these models are used to provide forecasts up to several days into the future with a considerable level of confidence, as well as to project or at least to estimate future climate developments for the decades and even centuries to come.

A meteorological model first of all consists of a so-called 'dynamical core' that is set up by the basic equations of three-dimensional motion and thermodynamics of air masses formulated as differential equations and cast into computer code employing certain methods of spatial (or spectral) and temporal discretization (Haltiner and Williams 1980, Holton 1992, Jacobson 2005). Furthermore, various physical processes, such as moist physics (phase transitions of water), or the effects of radiation, have to be taken into account by a set of specific routines.

Depending on the effective spatial resolution, set by the discretization (or by the truncation in spectral models, respectively), some processes in the atmosphere can not be captured directly by the basic equations. Here so-called parameterizations have to fill in (Stensrud 2007). Moist convection (Emanuel 1994), for example, is characterised by spatial scales that are much smaller (< 10 km) than the typical resolution of a global model (> 100 km) and thus has to be parameterized by an additional routine. This 'convection parameterization' has to realistically estimate the sub-scale convective activity within each single model cell based on the explicitly resolved variables (temperature, moisture, etc.). A variety of approaches resorting to different closure assumptions and trigger functions is used to decide about the occurrence and the intensity of convection within the simulation (see also section on convective parameterizations in chapter 3). Particularly important for the overall simulation is the feedback to the explicitly resolved variables generated by convective (or other subscale) processes. This is done mostly with the help of an idealized cloud model and/or an idealized post-convective thermodynamic profile. Furthermore the lower boundary condition of the atmosphere has to be provided by a landsurface (Dickinson 1992, Sellers 1992) and (especially for global climate models) ocean module (Niiler 1992, Haidvogel and Bryan 1992, Marsland et al. 2003) that ideally is interactively coupled to the atmospheric part of the overall model. The exchange of mass and energy between atmosphere and underlying surface is accounted for by the planetary boundary layer scheme (Stull 1988, Garratt 1994) that simulates turbulent exchange in the lowermost part of the atmosphere according to the prevailing stability regime governed essentially by, first of all, the thermodynamic profiles, wind shear and surface roughness. Whereas all processes in a complex model are more or less strongly intertwined, some of these schemes also interact directly with each other as illustrated in figure 2.1 (taken from Dudhia 2005). The high degree of complexity of such models allows on the one hand to capture the natural behaviour of the atmosphere quite realistically and such allows for quite reliable weather forecasts and climate projections (Randall 2007). On the other hand this complexity sometimes also might obstruct ones view onto the very basic processes—that is why 'simple', more conceptual models should still be granted their right to exist.

The following subsections will go into somewhat more detail of the individual models.

2.1 Global reanalysis / ECMWF's ERA40 project

Climatological studies require high quality, consistent long time data sets of observed global meteorology for a variety of tasks, such as identifying trends (Greatbatch and Rong 2006, Wang et al. 2006), driving RCMs or impact models and last but not least the verification of climate models (Randall 2007). The ECMWF accordingly compiled all available observational data and processed them using a frozen state-of-the-art global

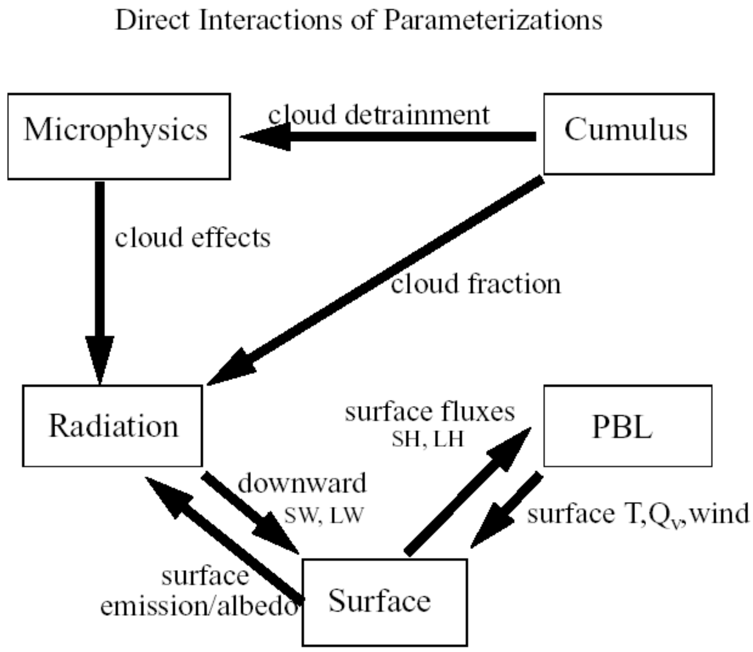


Figure 2.1: Direct interactions of parameterizations (from Dudhia 2005)

data assimilation system to accomplish an about 40-year long record of consistent global analyses of atmospheric fields (Uppala et al. 2005). This so-called re-analysis served as an 'optimal' observation-based input data set to the regional model in this study. In the following the concept of a meteorological (re-)analysis will be briefly explained.

First of all, daily operational analyses of the global atmospheric state are essential to provide highly realistic initial conditions for numerical weather prediction. The analysis is performed by combining a short-range global model forecast, giving reasonable background information on the current state of the atmosphere, and the assimilation of considerable amounts of observational data. The whole procedure usually comprises a set of 6-hourly consecutive cycles applying e.g. variational methods (Andersson 1998, Klinker 2000) and appropriate cost functions to minimize errors. The optimized analysis then serves as the initial condition of the next step. Essentially, this allows for the interpolation of observations (irregularly distributed in space and time) to give a realistic and consistent representation of the three dimensional global atmosphere and its evolution over a certain period in time. Possible inaccuracies of the numerical model are to some extent inherited by the analysis, particularly in data-sparse regions. The more numerous (in space and time) observations are, the less the model errors will affect the results.

The operational analyses, i.e. the 'initial conditions' for operational weather forecasts, are routinely archieved at the respective meterological centers, such as the ECMWF (European Centre for Medium-Range Weather Forecasts) or NCEP/NCAR

(National Centers for Environmental Prediction, National Center for Atmospheric Research, USA). Thus, continuous global datasets are in principle available for climatological studies. However, over the last decades various approaches implemented in numerical models and data assimilation systems underwent substantial improvements. This progress was not the least stimulated by the fact, that more and more observational data and even fundamentally new sources of observations and measurement techniques came on hand, such as a variety of instruments on satellites. This lead to comprehensive adaptations of the overall procedure in operational analysis, implicating systematic discontinuities in the respective timeseries, making them hard to use for long term studies.

Consequently, the ECMWF as well as NCEP/NCAR (Kalnay et al. 1996) decided to reprocess all available data comprising the last four to five decades with an updated version of their respective analysis systems, i.e. to perform a so-called re-analysis. Naturally, it is not possible to employ a current full-fledged, state-of-the-art operational version of an analysis system for such an enormous amount of data due to its substantial computational demand. Thus, compromises in terms of, e.g., resolution and the complexity of variational methods had to be made. The spectral resolution accordingly was set to T159 (truncation for wavenumber 159, corresponds to a horizontal resolution of about 120 km) for the ERA40 reanalysis compared to the operational resolution at that time of T511 ($\approx$ 40 km).

Figure 2.2 gives an idea of the worldwide distribution of observation sites, examplified for radiosonde stations. Obviously the operational network is much denser in the northern hemisphere than in the southern hemisphere, and, of course, over land than over the oceans. Figure 2.3 illustrates the quality of ERA40 data on the basis of background and analysis fits to observations using the example of surface pressure gathered by the SYNOP and SHIP observational network (Uppala et. al 2005). As could be expected from global data availability, that can be inferred from figure 2.2, the reanalysis generally performs better in the northern hemisphere compared to the southern hemisphere. However, a substantial improvement can be noticed over the whole ERA40 period. This has to be ascribed to overall improvements of the global observational system. Satellite data, for example, where first used from 1973 on, compensating for the lack of in situ measurements, which is reflected by the corresponding gain in accuracy of the analyses particularly for the southern hemisphere (Sturaro 2003). Thus, towards the end of the ERA40 period the performance of the reanalysis presents itself similar for both hemispheres (Sterl 2004).

The ERA40 reanalysis as well as the NCEP/NCAR reanalysis generally show reasonable performance in terms of sea level pressure, 500-hPa height, and temperature at 2 m, 500 hPa and 100 hPa (Greatbatch and Rong 2006). Both datasets agree strongly especially over Europe. First of all over North Africa and Asia, however, distinct discrepancies get obvious in the study of Greatbatch and Rong (2006) for surface layer pressure and 500 hPa height. For 2-m temperature discrepancies are also

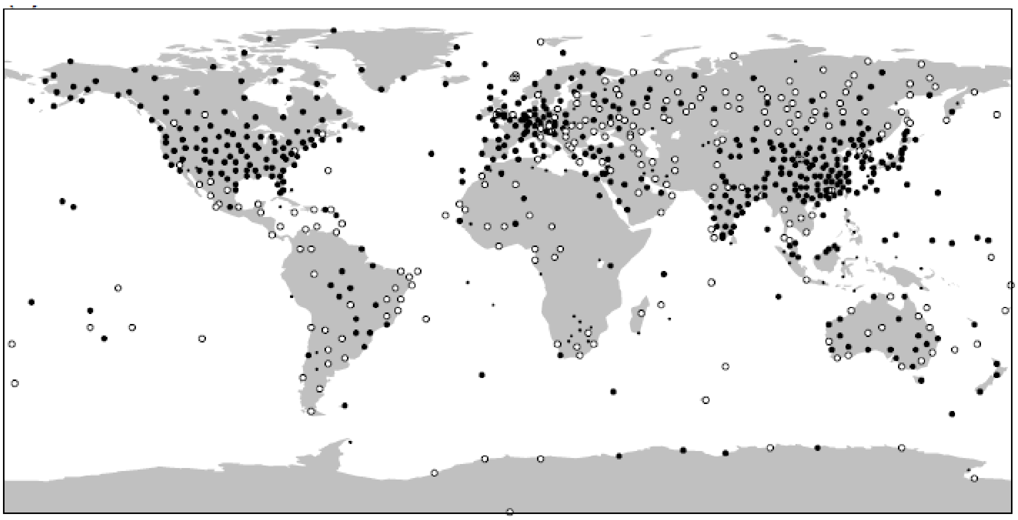


Figure 2.2: Radiosonde stations operational in 2001 (from Uppala et. al 2005); solid circles: at least three reports every 2 days (on average), open circles: reports at least once every 2 days, small dots: reports at least once per week.

found for the Pacific, the Arctic and parts of the American continent. Discontinuities for temperature are detected in the mid and upper troposphere of the tropics in the NCEP/NCAR reanalysis, that are ascribed to problems arising from the introduction of satellite data in the late 1970s (Sturaro 2003). In terms of cyclone activity ERA40 and the NCEP/NCAR reanalysis show good agreement over northern Europe and over eastern North America (Wang et al. 2006). Wang et al. (2006) suggest, that the higher resolution of ERA40 particularly allows for a better representation of extremes related e.g. to small-scale dynamics and cyclogenesis. Thus, together with its 'updated data assimilation system and more/improved assimilation data assimilated' the ERA40 dataset should be preferred to the NCEP/NCAR reanalysis, especially over Europe.

Naturally, ERA40 does not mark the very end of re-analysis efforts. The next step in this field is made by the ECMWF with its so-called ERA-interim re-analysis product (Dee et al. 2011), that offers some improvements based on experiences from the ERA40 project. Amongst others it is characterized by a considerably higher resolution (T255), covering the time from the year 1989 to present. Thus, it will be a highly valuable data set for a variety of future projects on climate (change), as soon as it spans a sufficiently long period of time.

2.2 Global climate models / ECHAM5

For projections into the future global climate models have to be operated running largely free, i.e., naturally, without incorporating observational input.

A modern, state-of-the-art global climate model (Randall 2007) generally consists of

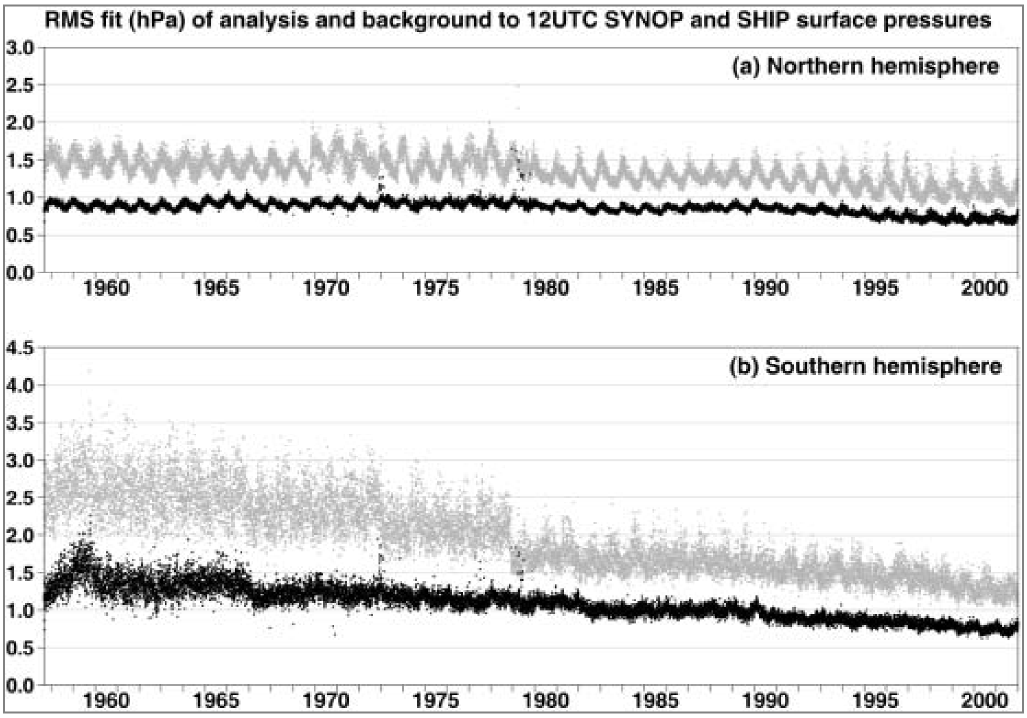


Figure 2.3: ERA40 RMS background (grey) and analysis (black) fits to extratropical SYNOP and SHIP measurements of surface pressure (hPa); (from Uppala et al. 2005)

a combined model of the atmospheric (Kiehl 1992) and the oceanic general circulation (Haidvogel and Bryan 1992), that are interactively coupled to each other (Schneider 1992, Meehl 1992). The overall system is driven by the incoming solar radiation, that is determined by solar activity and the orbital parameters, i.e. the relative position and orientation of the planet Earth to the sun (Roe 2006). Whilst weather forecast models and climate models are constructed basically in a quite similar way, their respective purposes and thus particularly some of the relevant timescales are distinctly different (Le Treut 2007). Thus, the results of climate simulations have to be evaluated on the basis of long term means and the corresponding variances and variabilities over, at least (ideally), 30 years. Still, also in climate mode the simulation itself should be as accurate as feasible for each single point in simulation time. This is valid in a sense, that for every model time step the simulation has to give a realistically possible solution for a certain path within the multi-dimensional phase space of the overall system. This specific solution, however, calculated for a point in time even several years after initialization, naturally is not verifiable against observations for a certain date in reality. In other words: there is no weather forecast initialized today (which would be some day in 2011) that gives valid information on whether it will rain or not at my hundredth birthday barbecue. At most, and hopefully, there are some reliable probability distributions, gathered from ensembles of simulations (Cubasch 1994, Barnett 1995) that might have changed with some reasonable degree of predictability thitherto.

The different relevant timescales of weather forecasts and climate models brings about some consequences for the necessary relative accuracy required by the respective model concerning some of its routines and/or input datasets and parameters. An operational forecast model, for example, does depend strongly on the initial condition of the atmosphere, that has to be provided by a highly accurate analysis system, as it will affect the evolution of the atmosphere over the next few days to a large extent (Lorenz 1963, 1975). In contrast, the atmospheric initial condition for a global climate model only needs to be reasonably realistic as this piece of information, due to its intrinsic timescale of several days, will practically be worn away completely over the long time of integration of at least several years (Collins 2002). The three-dimensional initial conditions of the oceans, on the other hand, are in principle of utmost importance for global climate simulations, as some of the relevant timescales here fall in the range of years, decades and centuries (Rahmstorf 2002, Jungclaus 2005) and thus are quite similar to the simulation times of global climate studies. However, one of the major challenges in climate projection still consists in quantitatively determining the current state and the temporal evolution of the global oceans by observations in a correct and comprehensive way (Gleckler 2006). Recent projects try to close this huge information gap by a constantly increasing armada of automated, free-floating buoys, that, during their journey through the oceans, continuously run vertical profiles recording data on, mainly, temperature and salinity (e.g. Thomas and Joyce 2010).

Furthermore, processes with long intrinsic timescales, such as encountered in the oceans, with its long distance transports of huge masses of water (Rahmstorf 2006), its enormous heat capacity and transport of heat (Jungclaus 2010), and its storage capacity for greenhouse gases (Rygg 2009), have to be captured by adequate simulation modules. An operational forecast model or atmospheric analysis system, in contrast, does not depend on its own ocean model and rather might ingest observed sea surface temperatures from an external source. Further processes relevant for the atmosphere and with long typical timescales are found, for example, in the biosphere, particularly on the landsurface, with its vegetation that interferes with the carbon cycle (Aber 1992, Cox 2004). Also the importance of marine plankton and organic matter in general should not be underestimated concerning its influence on carbon storage and on the carbon cycle (Najjar 1992, Sarmiento 1992, Le Quéré 2003). Not the least the cryosphere, i.e. the immense masses of ice stored first of all in the polar regions (Koenigk 2009), in glaciers all over the world and particularly in Greenland (Jungclaus 2006) has to be accounted for in global climate simulations (Hibler 1992, van der Veen 1992). Thus, over the last decades, based on an increasing knowledge of the climate system, more and more processes were incorporated into the models (Denman 2007).

To make things even more complicated, man influences the climate system and its evolution, mainly by anthropogenic emissions of greenhouse gases (Glantz and

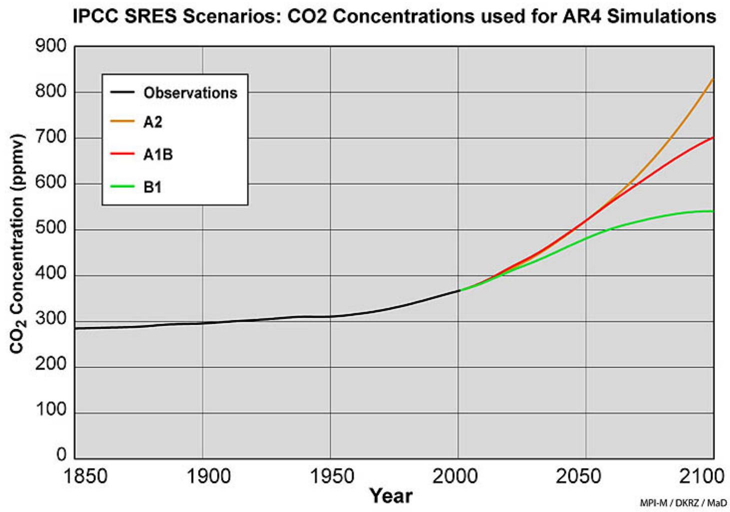


Figure 2.4: Atmospheric CO_2 concentrations as observed (1850-2000) and according to IPCC emission scenarios A2, A1B, and B1 (from Roeckner et al., 2006a)

Krenz 1992, Forster 2007). These emissions interfere directly as well as indirectly with the atmospheric radiation balance, the natural atmospheric chemistry and chemistry-transport processes (Turco 1992, Brasseur 1992). Thus, also socioeconomic aspects, processes and evolutions, governing man-made emissions, have to be taken into account in climate change studies. This is where the IPCC ties in with a set of possible future socioeconomic scenarios for the 21st century, such as in the fields of global population growth and industrial production as well as concerning the possibility of new technologies and new energy sources. The IPCC accordingly compiled a set of emission scenarios, the so-called 'Special Report on Emissions Scenarios' (SRES scenarios, Nakićenović and Swart 2000). They are subdivided in four alternative scenario families, thus trying to cover a wide range of possible socioeconomic developments. The various aspects of each scenario are then condensed into future emissions, which results in a correspondingly wide range of future greenhouse gase concentrations, i.e. first of all of carbondioxide as depicted in figure 2.4. The corresponding concentrations are prescribed to the global simulation models as components of the external forcing (Washington 1992, Meehl 2007), resulting in more or less dramatic increases of the global mean temperatures (cf. results of corresponding ECHAM5 simulations in fig. 2.5). Furthermore, human activities affecting, for example, landsurface and vegetation (e.g. deforestation, irrigation, etc.) can in principle also be incorporated externally into the simulations by gradually readjusting the corresponding parameters of the landsurface module (Feddema et al. 2005).

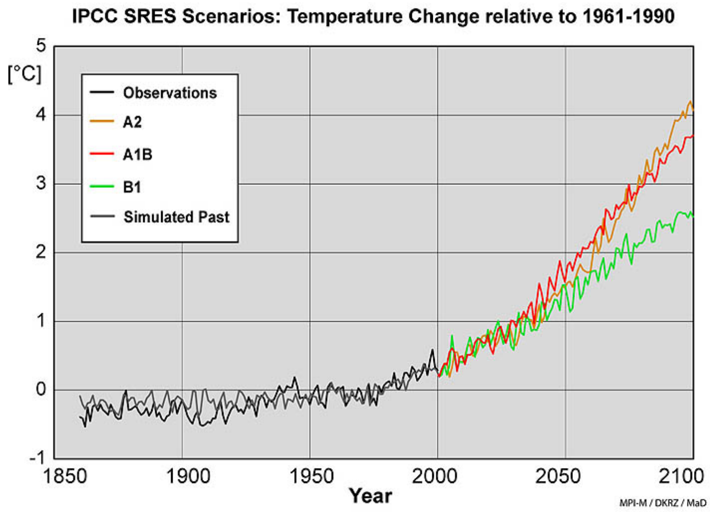


Figure 2.5: Temporal evolution of global mean near surface temperatures simulated by ECHAM5; difference to mean of the years 1961-1990 (from Roeckner et al., 2006a)

ECHAM5 is the specific global climate model, that's simulation results are used within the present study as driving data for the regional model MM5. It has been developed at the Max Planck Institute for Meteorology and is based on the ECMWF's general circulation model (Roeckner et al. 2003, 2006a). Thus, ECHAM5 is rather close in its formulations to the model underlying the ERA40 dataset, that is used for the sensitivity and reference experiments of this study—a circumstance which is advantageous in terms of data handling and processing, due to the similar data structure, and in terms of comparability of results.

ECHAM5 is applied for the very distant past (Jansen 2007) as well as under present day climate conditions to gain general knowledge of the climate system and for evaluation purposes (Randall 2007). Studies into the comparatively near future, i.e. the 21st century, are performed to give some insight into the possible future development of the natural environmental conditions relevant for the prosperity of mankind (Roeckner et al. 2006a, Meehl et al. 2007). In a paleoclimatic study Otto et al. (2009a, 2009b) reproduced reasonably well, compared to other model studies, the differences between pre-industrial and mid-Holocene climate using ECHAM5. Furthermore, they were able to determine the impact of atmosphere-ocean and atmosphere-vegetation feedback effects in response to orbital forcings in the context of mid-Holocene northern hemisphere insolation. For present day climate conditions Roesch and Roeckner (2006) assessed ECHAM5's ability to capture the annual cycle and interannual variability of snow cover and surface albedo (a key variable in the climate system) against ground-based and remote-sensed climatologies. They found ECHAM5 to reproduce these variables with reasonable accuracy on the hemispheric and continental scale. Lin et al. (2006) investigated the performance of 14 IPCC AR4 climate models in terms of convective signals. Here, ECHAM5 showed a comparatively high fidelity in simulations of the Madden-Julian oscillation. In a comparison study on the climate-carbon cycle feedback (Friedlingstein 2006) ECHAM5 agrees well with 10 other global climate models when forced by historical emissions. Furthermore, ECHAM5 here confirms the alarming finding that under future climate change the the Earth system's efficieny to absorb the anthropogenic carbon perturbation will probably be reduced. ECHAM5 also performs reasonably well in the context of coupled atmosphere-ocean simulations on the thermohaline circulation under increasing atmospheric CO_2 concentrations that have been conducted as part of the coupled model intercomparison project 'CMIP' (Gregory 2005). Thus, in summary ECHAM5 presents itself in manifold respects as a highly valuable member of the global climate model 'family', taking part in extensive studies also within the scenario framework set by the IPCC.

Roeckner et al. (2006b) investigate the impact of different resolutions (horizontal and vertical) on ECHAM5's simulation results. The specific combination of horizontal and vertical resolution turns out to affect the simulation of the large scale flow considerably. The resolution of T63L31 (truncation for wavenumber 63 corresponding to $\approx$ 300 km, 31 vertical levels), however, proves to be a reasonable compromise in view of computational demand and realistic simulation results. Paricularly storm tracks in the whole northern hemisphere agree well with corresponding ERA40 data (Bengtsson et al. 2006). Bengtsson et al.(2006), though, still suspect larger differences for smaller regions—a circumstance that proves to be quite important for the present study, as will be shown later.

All ECHAM5 simulations used within the present study are performed at a resolution of T63L31. The atmosphere is coupled to the ocean model MPI-OM GR1.5L40 (Marsland 2003, Gregory 2005). Present day climate simulations of ECHAM5 as well as data from a simulation under an A1B (i.e. moderate) emission scenario, as conducted for the fourth IPCC assessment report, are evaluated here in the context of regional climate modelling.

2.3 Regional climate model MM5

The global datasets (from ERA40 and ECHAM5) are taken to drive the regional model MM5 (Grell 1994, Dudhia 2005). Performing additional global simulations would have been beyond the scope of this study. The focus here is on adapting, operating, and validating the MM5, a so-called 'limited area model' for our region of interest, i.e. the upper Danube Catchment and the central Alpine area. MM5 practically gets 'nested' into one of the global models/datasets. Apart from an intriguing proof-of-concept study from Dudhia (2002), where a special version of MM5 is expanded to a global version by the means of two overlapping hemispheric model domains, the standard MM5 cannot be run in a stand-alone mode without comprehensive external meteorological input data. It depends on initial conditions covering its overall, 3-dimensional simulation domain and furthermore on a continuous supply of (reasonably at least 6-hourly) lateral boundary conditions.

MM5 comes with a multiple nesting capability that permits to focus step-wise successively on a region of interest with an increasing resolution (for interactive nests with a fixed factor of three) for each nesting level.

In the horizontal the grid resorts to a so-called Arakawa-Lamb B-grid staggering, with scalar variables (temperature, humidity, etc.) and vertical velocity defined at the center of each grid box and horizontal wind components at the corners, respectively. This type of staggering showed advantages over other grid types in terms of efficiency as gets reflected by a comparatively large possible time step allowing for numerically stable integrations and hence saving computational resources (Arakawa and Lamb 1977, Haltiner and Williams 1980).

The vertical levels are defined by a terrain following dimensionless σ-coordinate:

$$\sigma := \frac{p_0 - p_{top}}{p_{sfc} - p_{top}}. \tag{2.1}$$

with p_0 being a predefined vertical profile of pressure, and p_{top} and p_{sfc} the constant pressure at the top lid of the model and at the surface, respectively. The time independent reference state is defined by an idealized temperature profile in hydrostatic equilibrium. The values of sigma range in between 0 (model top lid) and 1 (surface), while each model level in between is labelled with a fixed value of σ. The spacing between levels usually is set much denser near the surface, i.e. within the boundary layer, thinning out towards the model top lid. The lowest coordinate surface with $\sigma = 1$ tightly follows the underlying orography, whereas the top lid level is perfectly flat. Variables are staggered in the vertical as well, with almost all variables defined at the middle of each layer (referred to as 'half-sigma-levels') and only vertical velocity allocated to the 'full-levels'.

The hydrostatic approximation, where the pressure in each grid box is completely determined by the overlying air's mass, does no longer hold for comparatively small horizontal grid sizes. This fact is calling for an additional term in the dynamics of the non-hydrostatic MM5, i.e. a vertical acceleration that contributes to the vertical pressure gradient, which in turn gets reflected by extra three-dimensional predicted variables, namely the pressure perturbation from the reference state together with vertical momentum (Dudhia 1993). In the (meanwhile obsolete) hydrostatic version of MM5 the vertical velocity has been calculated diagnostically, using the incompressible continuity equation.

MM5 is applicable for any region of the globe and accordingly offers three options for map projection in its 'terrain' preprocessor: polar stereographic for domains situated around one of the poles, mercator for equatorial regions, and lambert conformal for the mid-latitudes—the method of choice for the simulation area of this work, i.e. central Europe. 'Terrain' also ingests data on terrain elevation, soil, land use and vegetation types and interpolates them onto the chosen domain and its rectangular grid. For every grid box also map scale factors, reflecting distortions due to the projection and thus important in the calculation of horizontal gradients, latitude and longitude, and a Coriolis parameter are determined.

The next preprocessor, 'regrid', handles meteorological input data valid on pressure levels and on the surface. The minimum set of variables required for MM5 comprises sea-level pressure, wind, temperature, relative humidity and geopotential height, given at a minimum set of ten mandatory (pressure) levels and at the surface. The data are cut out for the domain defined with the help of 'terrain' and get interpolated horizontally onto the MM5 grid.

The last preparatory step for an actual MM5 simulation is accomplished with the help of 'interp', i.e. the preprocessor to interpolate input data in the vertical to the sigma-levels and eventually generating the necessary specific input files for MM5, i.e. the file holding the initial condition with various three- and two-dimensional fields covering the overall model domain and the file with (e.g. 6-hourly) lateral boundary data for the whole simulation period. The boundary data are given for the four outer rows at each side of the domain to allow for a smooth gradual blending into the simulation area. Furthermore, also continuous lower boundary conditions have to be provided to MM5, such as sea surface temperatures, if applicable, and some more variables (e.g. snow cover) depending on the complexity of the land surface model used. Once all these files, repectively variables, are available the forward integration in time can be started.

The temporal finite differencing of MM5 resorts to a long as well as to a short time step, and thus to a so-called time-splitting scheme (Dudhia 1993). Most of the terms are handled with a long time step in a second-order leapfrog scheme to accomplish the forward integration from time step n-1 to n+1 with the tendencies valid at time n. Fast processes or phenomena, such as sound waves, have to be treated by a shorter time step for the sake of numerical stability with a more frequent update of the related tendencies. Within MM5 typically one leapfrog time-step is broken down into four fast time steps. Comparatively slow processes, on the other hand, may allow for considerably infrequent calculations, such as some radiation schemes that are only called every 10 to 30 minutes, saving valuable computational resources. Furthermore, also implicit time schemes, that are virtually independent of the time step, are quite convenient where applicable. In MM5 such a scheme is implemented especially for 1d-column calculations of fast processes such as vertically propagating sound waves. The 1d-calculations here allow to set up the corresponding system of equations in form of a tridiagonal matrix that is readily to be solved. The resolution in the vertical usually is much higher compared to the horizontal dimensions. Thus, here numerical stability could otherwise only be achieved by an explicit time scheme with a very short time step resulting in unduly high computational costs.

In the course of a MM5 simulation all relevant routines (advection, radiation, boundary layer, convection, etc.) are called successively to calculate the tendencies, for all variables to be predicted, due to each of the respective processes. At the end of an integration cycle all these tendencies are summed up and the state of the overall system for the new point in time is determined.

The MM5 modelling system originally was developed as a research model with various options, respectively approaches, in model physics, allowing for an individually optimized configuration of the components decisive for the intended task—a great advantage particularly also for the present study. The actual physics schemes used, adapted and investigated in the context of this work will be discussed in more detail in the following chapter.

Chapter 3

Experimental Setup

The previous chapter gave some basic information on meteorological models in general and already some deeper insight into MM5. Now the specifics of MM5 as used for this study shall be presented. This concerns the simulation domain as well as the configuration of MM5 with respect to the available physics options. Moreover, some minor modifications concerning model deficiencies detected in preparatory simulations will be addressed in a short survey. Furthermore a straightforward method, newly implemented for this study, to keep the model simulation close to the driving input large scale fields will be explained and briefly discussed. Finally the observational basis with respect to precipitation and near surface temperature is presented. Particularly for precipitation the ambiguities of available observational datasets is discussed and a somewhat non-standard error measure is introduced, that later on will prove highly appropriate to assess the model's performance.

3.1 Model domain and Upper Danube Catchment

The MM5 system offers a virtually free choice in the definition of the simulation domain. For the use in GLOWA-Danube it naturally has to cover quite amply the comparatively small upper Danube catchment. Thus, the model domain covers most of the European continent at a horizontal resolution of 45 km with 79 gridboxes in west-east and 69 gridboxes in south-north direction, with the lower left corner at (8.2 W, 35.6 N) and the upper right corner at (43.2 E, 61.0 N), allowing the model to capture the relevant synoptic environment. In the vertical 29 layers are used up to a top lid pressure of 100 hPa with enhanced vertical resolution in the lower atmosphere to enable a satisfying representation of the exchange processes in the planetary boundary layer. Boundary data are taken from the ERA40 ECMWF re-analysis (Uppala et al. 2005). All simulations are given a spinup time of six months. This is done in order to allow the 'slow' landsurface module with its 'long-time memory' for temperature and moisture, that are only coarsely initialized with data taken from the global datasets, to adjust to the meteorological forcing of the regional model. Following the spinup time the model is integrated over the whole ten years of 1991 to 2000 for the reference experiment (cf. chapter 4) in one continuous simulation run, just like for each of the other long time simulations (driven also with ECHAM5 output, cf. chapter 5).

3.2 MM5: the specific configuration used

The regional model employed for this studies is, as already mentioned above, the well known and widely used Pennsylvania State University / National Center for Atmospheric Research Mesoscale Model MM5 (release 3.7.3) (Grell 1994). MM5 offers a variety of parameterizations to treat the different physical processes in the atmosphere. The most promising and eventually most satisfying configuration for the purposes of the present work was identified in a series of preparatory test simulations not shown here. The optimization process focused first of all on simulated precipitation and secondly on near surface temperature. Various options for various processes were tested.

Accordingly for the experiments presented in this work the model was configured as follows. The planetary boundary layer is parameterized with a level 2.5 Mellor-Yamada scheme (Mellor and Yamada 1974), basing on the prediction of turbulent kinetic energy, that originally was developed for the ETA model (Janjic 1994). The PBL scheme is coupled to a thin surface layer where vertical fluxes are calculated with the help of the Monin-Obukhov similarity theory. The so-called cloud radiation scheme implemented by Dudhia (1993) accounts for direct interaction between long wave as well as short wave radiation and resolved clouds. The explicit mixed phase cloud microphysics scheme follows Reisner et al. (1998) and allows for the coexistence of water vapour, (supercooled) liquid water, ice, and snow. Thus, it also implements processes such as slow phase transitions, ice accretion and coagulation, eventually contributing to rain and snowfall. Deep moist, precipitating convection is accounted for by the Kain-Fritsch-2 scheme (Kain and Fritsch 1990, 1993; Kain 2004) that, naturally, is also activated for grid boxes that are not saturated. Beyond these physics schemes also the truly horizontal numerical diffusion scheme, implemented by Zängl (2002) and publicly available since model version 3.7, is used. To obtain a realistic annual cycle of the lower boundary conditions, a sophisticated landsurface-vegetation module, the so-called NOAH-LSM (Chen 2001a, 2001b), is employed with some modifications as indicated in the next section. Furthermore, for the sensitivity experiments discussed in the first section of chapter 4, also the Grell (1993) and the Betts-Miller (Betts 1986, Betts and Miller 1986, 1993) cumulus convection schemes are tested, and the numerical horizontal diffusion formulated along the terrain-following sigma coordinate surfaces is investigated with respect to its influence on simulated precipitation.

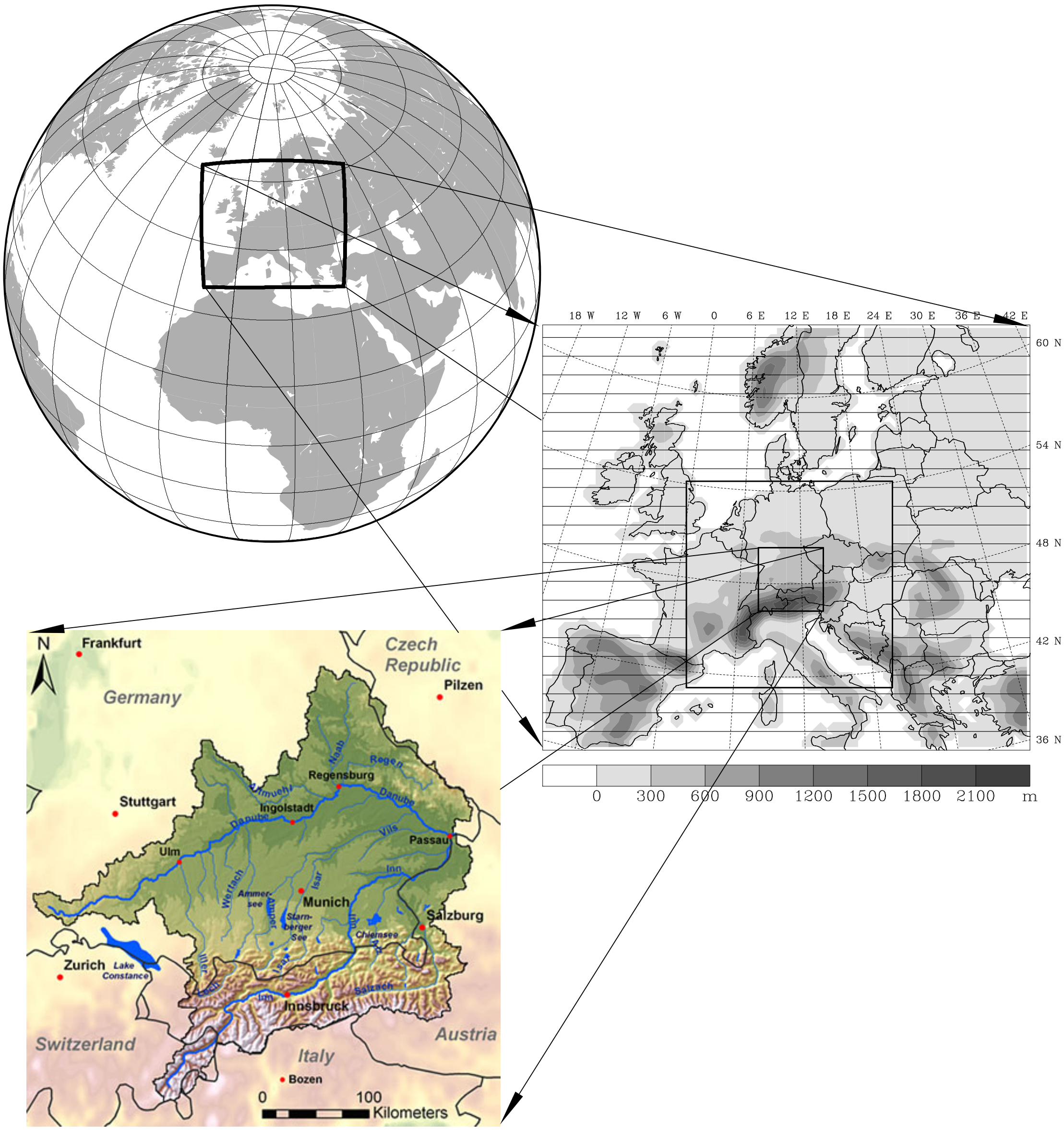


Figure 3.1: Domain of MM5 simulations with (model) terrain height (right). Observation nudging above the boundary layer was applied only within the hatched area (see text). Region of interest: the Upper Danube Catchment (lower panel, cf. Mauser et al. 2010)

3.3 Some notes on the convective parameterizations

The focus of the present study is on simulated precipitation. The generation of precipitation is strongly governed directly and predominantly by the convection parameterization. Accordingly, in chapter 4 a 'mini ensemble' of sensitivity experiments relying on three different widely used cumulus convection schemes is presented. Thus, a short overview of the main characteristics of the respective schemes will be given in this section.

According to Kain and Fritsch their parameterization can be partitioned into three parts: the trigger function, the mass flux formulation, and the closure assumption. The scheme is triggered by adding a temperature perturbation (or effectively a perturbation of vertical velocity) to a vertical layer beginning at the surface level. If this perturbed 'parcel' is not able to reach its lifting condensation level (LCL) the base of the potential source layer for a convective cloud is moved upwards one model level and the test gets repeated. If the LCL is reached in one of the iteration steps the unperturbed parcel is allowed to rise, while entraining and detraining, as long as its vertical velocity is positive. The depth of this convective 'test cloud' at least has to be 4 km for the actual parameterization to be activated. Otherwise the whole sequential iteration falls back to the next test level to be perturbed. If the test parcel originates from more than 300 mbar above the surface the scheme decides on 'no convection' and moves on to the next grid box. The trigger mechanism is closely related to the mass flux formulation, or rather the (single-)cloud model of the scheme, as vertical motion and thus the cloud depth is strongly controlled by entrainment and detrainment. The entraining and detraining plume exchanges equivalent potential temperature and water vapour with its environment. Furthermore various additional moisture variables can be detrained from the cloud. Entrainment rates are higher for higher parcel buoyancy and a moist environment, whereas parcels with low buoyancy are prone to get diluted rapidly into a comparatively dry ambient atmosphere by high detrainment rates. Convective downdrafts driven by evaporation of condensed water within the cloud are designed more or less analogously to the updraft. Environmental subsidence or uplifting, respectively, compensates for the convective mass fluxes, thus inducing a feedback to the large scale variables. The closure assumption bases on the removal of 90% of the convective available potential energy (CAPE) that initially is calculated with respect to the undiluted parcel ascent, i.e. with constant parcel characteristics valid for the starting level of the updraft. The relaxation towards a neutral atmospheric profile is accomplished by inner-cloud and environmental mass fluxes with a time scale that ranges in between 30 and 60 minutes.

The Grell scheme is an Arakawa-Schubert (Arakawa and Schubert 1974) type scheme that resorts to an extremely simplified single cloud model not allowing for any lateral mixing with its environment. Thus the mass flux within the cloud, once determined, remains constant in the convective process. This is also true for the convective downdraft. Detrainment into the surrounding atmosphere only occurs at the cloud top, where the updraft reaches its level of neutral buoyancy, and correspondingly for the downdraft at the surface. Feedback to the explicitly resolved variables is accomplished by compensating vertical motions of the environmental air, thus redistributing moisture and temperature according to the respective large scale vertical profiles. The closure bases on a quasi-equilibrium assumption, i.e. the effect of convection only compensates the rate of destabilization due to the large-scale forcing and thus the inner-cloud mass fluxes are dimensioned to match this requirement without accounting for the total amount of CAPE.

The Betts-Miller scheme also bases on the idea of a quasi-equilibrium between large-scale forcing and convection. Betts and Miller, however, deduce a significantly different approach from this assumption to tackle the effects of convective activity. Convection essentially poses a strong constraint for realistic local vertical profiles as it acts, often quite vigourously, to stabilize the atmosphere. In nature the interplay with large-scale forcing leads to certain vertical structures of moisture and temperature, characteristic for a convective environment. Hence, the Betts-Miller scheme is not focussing on the convective process itself but rather on its outcome, i.e. a target atmospheric stratification estimated from appropriate observations to serve as a reference state. The parameterization hence directly performs an adjustment with a fixed time constant of 50 minutes towards the predefined quasi-equilibrium vertical profiles of temperature and moisture. The adjustment thus essentially represents an implicit calculation of the effects of convective mass fluxes. Consequently, the scheme has not implemented any cloud model, such as entraining and detraining plumes. It deliberately 'ignores' the complex processes of convection itself. This is based on the argument, that these processes are hard to observe in nature as well as hard to implement in sufficient detail in numerical models. Generally, the scheme depends strongly on the observational basis and on decisions on which of these observed profiles are valid and to be taken in consideration for the specific case to be simulated. Hence, this approach implies the somewhat awkward need (or convenient room—depending on the respective point of view) for calibration. This, however, should be avoided in principle as far as possible in physically based numerical models. Furthermore, corresponding to its very construction, the scheme lacks the implementation of convective downdrafts that, primarily in cases of severe convection, can strongly affect the resolved atmospheric environment. Last but not least, it has originally been developed for larger scales with rather homogenous environments and thus might not be perfectly well suited for areas characterized by complex, fine-scale orographic features.

3.4 MM5: some modifications

In the preparatory test suite some inaccuracies in the NOAH landsurface scheme have been identified. First of all, the transition from saturation vapour pressure over water to that over ice for temperatures below the freezing point had to be implemented. This was necessary to obtain a reasonably realistic deposition of rime at the surface and to prevent the persistent occurrence of near-surface fog in the model. In addition, the calculation of snow cover fraction had to be modified to prevent trees and higher shrubs from vanishing completely at snow water equivalents above 80 mm. This deficiency previously led to an unrealistic calculation of soil heat transfer and to too low surface temperatures particularly in Alpine forested areas. Furthermore the vegetation fractions provided by the USGS (U.S. Geological Survey) datasets to the landsurface scheme objectively proved to be too high in the simulation area; an overall reduction by 30 percent to more adequate values helped to improve the simulation of summertime near surface temperature substantially.

3.5 Masked FDDA

In a standard setup of MM5 only the five outer rows and columns of the grid boxes on each side of the simulation domain are provided with lateral boundary data from the driving meteorological dataset. The information gets fed into the simulations via nudging terms in the appropriate equations, with decreasing weights (factor 1 for outermost boundary, decreasing linearly to 0 within the next four gridpoints) towards the inner part of the domains. To keep the regional model close to the analyzed large-scale circulation, in the setup for the present study additionally a relatively simple version of so-called 'four dimensional data assimilation' (FDDA, Dudhia 2005, Haltiner and Williams 1980, not to be confused with the much more complex and costly 4DVAR, i.e. four-dimensional variational assimilation) is applied throughout the whole simulation on a rather wide area between the boundaries and the inner region of the model domain (cf. Fig. 3.1). There, additional so-called 'Newtonian relaxation' terms (Haltiner and Williams 1980) are introduced to the equations of MM5 to 'nudge' (Grell 1994) the model solution towards 6-hourly data of the EMCWF reanalysis following the formulation of the standard FDDA option in MM5 (Stauffer and Seaman 1990). This is done for wind, temperature, and water vapor, but only above the planetary boundary layer. In the inner part of the simulation area covered by 33 x 33 grid boxes, no nudging is applied at all to allow the MM5 to find an independent solution. Verification naturally only is done in this inner region of the domain where no FDDA is applied. Using this 'masked' FDDA, substantially better results in daily rainfall amounts for the verification area (southern Germany and parts of the German and Austrian Alps) are achieved compared to simulations without any nudging. Figure 3.2 accordingly shows scatterplots for the four year period of 1996 to 1999. For all seasons generally a tendency to a slight overprediction of weaker rainfall events gets obvious, that, however, do not substantially contribute to the total precipitation amounts. The higher the daily rainfall amounts the better is the correspondence between simulation and observation. The most impressive gain from applying masked FDDA can be drawn for spring pushing the correlation coefficient from a value of 0.69 to 0.86. The model obvioulsy encounters some problems to capture the daily precipitation events correctly without some additional information. This might be due to the comprehensive switch in circulation patterns between winter and summer entailing more convectively dominated situations in the warmer seasons compared to precipitation predominantly associated with frontal passages in winter. In winter consequently the benefit of masked FDDA is quite moderate. On the annual scale the correlation coefficient after all rises from 0.76 to 0.88. The simulations using masked FDDA were also used in parallel for another set of studies investigating the day to day performance together with a hydrological model where the additional information proved to be quite valuable. However, for the monthly or annual averages presented in this study, no significant impact on temperatures or rainfall amounts could be identified. Thus, the climatological behaviour of the MM5 can be regarded as robust against the application of masked FDDA.

3.6 Observational basis and validation methods

To validate the regional climate simulations presented in this study the focus is set on precipitation and 2-m temperature. These two variables are the most important ones for a great variety of subsequent climate impact studies. The necessary observation data are provided by the German Weather Service (DWD), the Austrian Weather Service (ZAMG) and the Austrian Hydrological Service (HZB). Figure 3.3 displays the distribution of the observational network for precipitation in a subdomain more or less covering the region of interest. No data are available for Italy and Switzerland, so the investigations have to be restricted to the German and Austrian parts of the Alps. In total around 1000 stations are at hand, providing daily rainfall amounts, and around 200 stations with hourly temperature data. A potentially problematic aspect is that the observations are distributed quite irregularly and that they have to be compared in some consistent way to the model data given on a regular grid. This means that either the observation data have to be aggregated onto the model grid or reversely the grid values of the model have to be interpolated to the original observation sites. As pointed out by Tustison et al. (2001) especially for rain gauge data, each method is associated with systematic errors depending on the data density and the model grid size. For rain this complication gets aggravated due to its high spatial variability. Thus, for rain the validation is extended to an alternative dataset which will be described in some more detail in the following subsection.

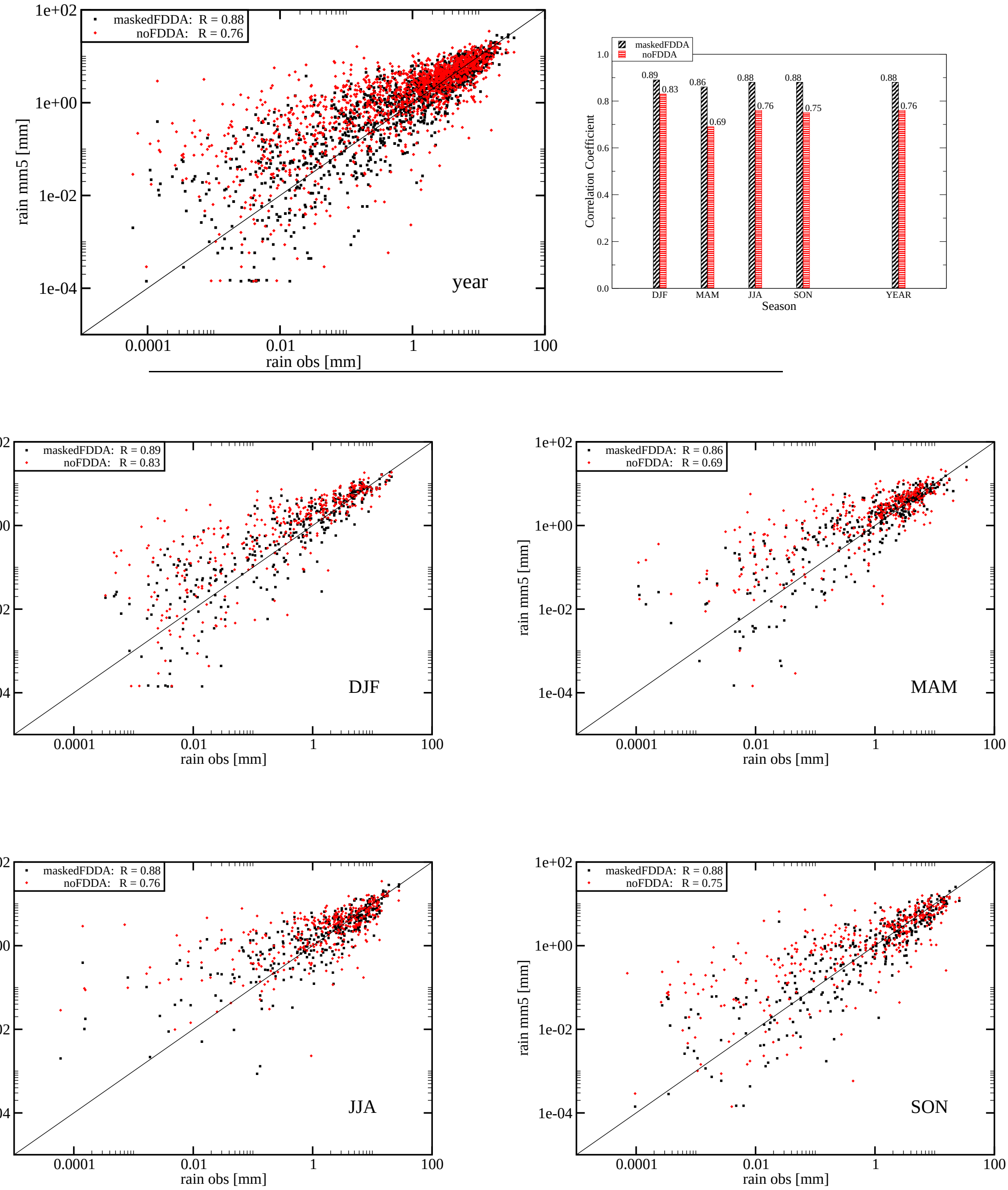


Figure 3.2: Scatterplots of simulated versus observed daily precipitation amounts (annual and seasonal for the years of 1996 to 1999) with ('maskedFDDA') and without ('noFDDA') masked FDDA and respective correlation coefficient ('R', summarized in upper right panel)

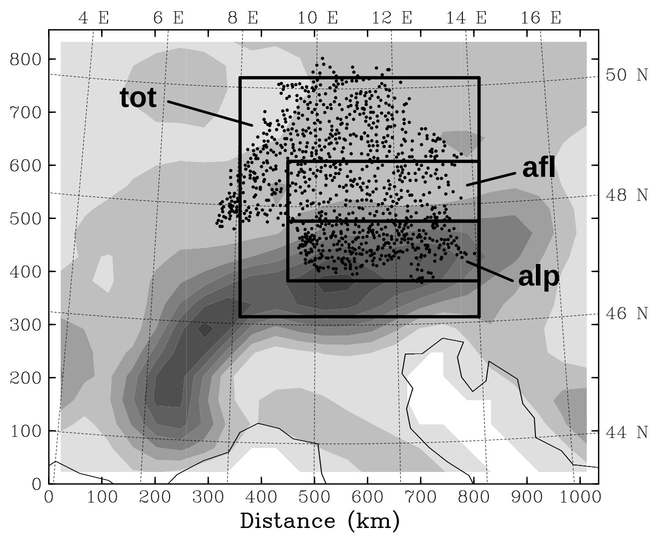


Figure 3.3: Observation sites (dots) for precipitation and three validation areas. Area 'tot' also indicates the coverage of the gridded observational dataset. For reasons of comparability precipitation for each of these areas generally only was verified on model grid boxes where sufficient data from both observational datasets were available. Contours of terrain height cf. Fig. 3.1.

3.6.1 Precipitation

In the case of rain verification is based on spatial averages of the rain gauge measurements, which are compared with the corresponding grid box values of the simulation. In Tustison et al. (2001) this is referred to as the 'point-to-area' method. This is adequate as the model with its comparatively coarse horizontal resolution of 45 km is naturally unable to capture the meteorological situation in detail on each observation site. This is especially true for rainfall in an area with a highly varying small-scale topographic structure as it is encountered in the Alpine region.

For rain simulation results are additionally compared to a gridded high-resolution dataset to account for the uncertain representativeness of the measurements available in the Alpine part of the region of interest. The observation sites in mountainous areas tend to be located in valleys rather than on mountain ridges for convenience, which probably leads to a certain systematic bias in areal averages when no further corrections are implemented. The gridded dataset is based on the high-resolution (2 km) precipitation climatology of Schwarb (Schwarb 2001, Schwarb et al. 2001). They derived their monthly climatologies of precipitation for the Alps by applying a modified version of the 'Precipitation-elevation Regressions on Independent Slopes Model' (PRISM) (Daly et al., 1994) that combines climatological and statistical concepts to the mapping of orographic precipitation. As this climatology refers to a different reference period (1971–1990), it has been merged with station data for the period of interest. A detailed description of this procedure can be found in Früh et al. (2006). For the purposes of the present study these highly resolved fields are again aggregated to the model grid boxes. The validation of simulated rain here is hence based on the one hand on simple spatial averages of station data and on the other hand on true areal means of gridded observation fields. Yet the second dataset, albeit based on highly sophisticated algorithms, still is not free of errors. For example, the limited representativity of the few available mountain stations in the eastern central Alps (Fliri 1975, Wastl and Zängl 2008) has the effect that the height regression applied in PRISM tends to overestimate mean precipitation in this area. Thus, as simple spatial averaging of raingauge stations tends to underestimate true areal means in mountainous areas (because most stations are located in valleys), in this work two different datasets are used, systematically spanning something like a 'mininum–maximum' interval for observed precipitation. The truth in terms of precipitation fallen in reality might lie somewhere in between. Note that in the context of the investigations presented in this study it is not intended to give any assessment of the relative quality of each of these two observational datasets.

Beyond the usual error measures like RMSE and bias also a non-standard error score is applied, which is referred to as normalized absolute error (NAE). The NAE represents the average of the absolute error weighted by the relative error and is defined as

$$NAE = \frac{1}{N} \sum_{i=1}^{N} \frac{(x_{obs,i} - x_{sim,i})^2}{0.5 \cdot (x_{obs,i} + x_{sim,i})} \tag{3.1}$$

where $x_{obs,i}$ and $x_{sim,i}$ stand for observed and simulated rainfall amount per grid box (index i) accumulated over a given time period (in comparison the RMSE is defined as $\sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_{obs,i} - x_{sim,i})^2}$).

Whereas the RMSE counts any deviation between simulation and observation in the same way, no matter how high the observed rainfall amount is, the NAE counts a given absolute error less for high rainfall amounts than it does for light precipitation. This provides a more meaningful assessment for fields with a high spatial variability. For the simulation series presented here, it is found that the NAE provides a much clearer discrimination between 'good' and 'bad' model configurations than the RMSE does.

The part of the simulation area where verification takes place is characterized by rather distinct variations in orography. Thus, besides considering the whole domain where observations where available also two different subdomains are analysed, i.e. the Alpine foreland and the Alpine part of the model domain (cf Fig. 3.3).

3.6.2 Temperature

For near surface temperature and dew point temperature the 'area-to-point' method in the nomenclature of Tustison et al. (2001) is used. This is meaningful because the density of available temperature data is quite comparable to the model meshsize, and because temperature generally shows much less spatial variability than precipitation. To account for the height-dependence of temperature, also a height correction is applied, based on the difference between station height and interpolated model height. However, this height correction is considered to be 'safe' only for height differences of up to 200 meters. Thus all stations exceeding this height difference are omitted. This eventually excludes most of the higher Alpine region from the evaluation of temperature. After all, up to 40 stations with hourly temperature data are considered in the verification area. Specifically, the validation procedure comprises the following two steps. First, for each station the locations of the four surrounding model grid box centres are identified, and inverse-distance weighted horizontal interpolation factors are calculated with respect to the geographical location of the station. Second, a correction for the difference between the actual station height and the corresponding interpolated model orography height is applied. For that, climatological vertical temperature gradients are estimated from the available radiosonde ascents of Munich, excluding ground-based inversions if applicable. Values between -0.4K/km and -0.5K/km are found in winter (night/day) and between -0.5K/km and -0.8K/km in summer, with spring and autumn ranging in between.[1]

[1] The concepts discussed in this chapter are also presented in Pfeiffer and Zängl 2010

Chapter 4

Validation of MM5 driven by ERA40 reanalysis data

The purpose of this chapter is to present and discuss the first necessary step in the evaluation of the regional climate modelling approach as devised for the GLOWA-Danube project. That is the critical assessment of the performance of the regional model itself. Thus, MM5 simulations driven by observation-based meteorological fields provided by the ERA40 reanalysis project will be analysed. First of all, the optimal configuration of MM5 with respect to simulated precipitation, the 'key'-variable of a hydrological project, has to be identified in the first section. This is done in a set of simulations, each of which continuously covering the four years of 1996–1999 that are typical, climatologically, in terms of precipitation for the 1990s. As discrepancies in simulated precipitation occur mainly in summer it is quite obvious to test different convection parameterizations in this set, or 'mini ensemble', of sensitivity experiments. It is somewhat less obvious that also the formulation of the numerical horizontal diffusion might play an important role in the model's rain generation. Both aspects are put into perspective to assess the relative influence on simulation results.

Once the most appropriate configuration has been identified the performance of this reference setup will be further scrutinzed in an extended simulation for the whole decade of the 1990s, also taking near surface temperature and moisture into consideration. This shall further confirm the findings of the sensitivity simulations.

4.1 Sensitivity tests concerning convection parameterization and horizontal numerical diffusion

In this section the results of a set of sensitivity experiments focussing on the influence of the convection parameterization scheme and the formulation of the numerical horizontal diffusion on simulated rain will be analyzed. The study is deliberately limited to the use of the unmodified convection schemes as they come with the MM5-system, because one primary goal of these experiments is to provide a given reference against which, amongst others, the impact of the diffusion scheme can be evaluated. Tuning or optimizing cumulus schemes is thus beyond the scope of this work.

Zängl originally implemented truly horizontal diffusion (or z-diffusion) to overcome major deficiencies in the dynamics of high-resolution simulations in mountainous terrain, i.e. valley wind circulations in the Inn Valley of the Alps (Zängl 2002). At first it was not obvious that z-diffusion would also play an important role in moist physics and thus in the generation of precipitation, particularly at the comparatively coarse mesh size of 45 km in the present study. First somewhat disappointing test simulations in the run-up of the present study, however, spurred the suspicion that terrain-following 'horizontal' diffusion in the Alpine area might have some substantial influence on simulated precipitation even at rather moderate resolutions. This motivated a closer analysis on this issue, the results of which are also presented in the following.

For the sake of efficiency, the sensitivity experiments are restricted to the years of 1996 to 1999. This four-year period got selected because its climatological properties concerning precipitation are closest to the full 10-year period of the reference experiment presented in the following section. In Fig. 4.1 validation results based on various error measures (bias, RMSE and NAE) are presented for six different MM5 configurations. Values for annual precipitation are considered separately for the total investigation area ('tot') and the two subdomains 'Alpine foreland' ('afl') and 'Alps' ('alp') as defined in Fig. 3.3. Here it should be pointed out that the area of the 'alp'-subdomain has about the same size as the 'afl'-subdomain (effective size depending on available observation sites, see Fig. 3.3) whereas the total area for the analyses is about four times larger than each of these two subdomains. This has to be kept in mind when trying to draw a balance for rain for the three domains. The validation is based on the two different datasets of observations presented above. The three selected schemes for cumulus convection are available within the MM5 modelling system as the Grell- (1993), the Betts-Miller- (1986a, 1986b, 1993) and the Kain-Fritsch-2-scheme (Kain and Fritsch 1990, 1993, Kain 2004), respectively. Figure 4.1 summarizes results for the original formulation of horizontal numerical diffusion along terrain following sigma coordinates as well as for the z-diffusion scheme. For convenience, the members of the 'ensemble' are denoted by capital letters 'G', 'BM' and 'KF' for Grell, Betts-Miller and Kain-Fritsch-2-scheme, respectively, and by the small letters 's'/'z' for σ-diffusion and z-diffusion.

The bias graphs in the left column of Fig. 4.1 indicate that both the convection scheme and the diffusion formulation have a profound impact on the simulated precipitation fields. Overall, the BM scheme tends to generate the largest rainfall amounts, followed by the KF scheme and the Grell scheme. The diffusion formulation has little impact on total average except in combination with the KF scheme, but comparing the results for the Alpine foreland ('afl') and the Alps ('alp') indicates a pronounced redistribution of precipitation related to numerical diffusion. Compared to the z-diffusion scheme designed to minimize systematic numerical errors, the σ-diffusion shifts precipitation from the Alpine foreland into the Alps, as might be anticipated from the notion that computing moisture diffusion along terrain-following coordinates entails an upslope transport of moisture (see discussion below). In comparison to observations, the BM and KF schemes tend to overestimate precipitation in the total domain whereas the Grell scheme is somewhat too dry. However, the KF-z run lies within the range of uncertainty spanned by the two observational datasets. In the Alpine foreland, G-z and all experiments employing σ-diffusion are too dry, whereas BM-z and KF-z are close to observations. Finally, BM-s grossly overpredicts rainfall in the Alpine domain, followed by BM-z and KF-s, whereas KF-z and G-s are within the range of observational uncertainty and G-z is too dry. Putting these pieces together, one can state that the KF-z setup (which is also used for the 10-year reference experiment) is closest to reality, whereas BM-s exhibits by far the largest errors.

This interpretation is corroborated by the RMSE and NAE scores (middle and right column), which in addition indicate that the z-diffusion runs generally show much better skill than the σ-diffusion runs. In almost all cases, the difference is largest in the Alpine domain, but the spread in the Alpine foreland also tends to be higher than in the total validation domain. Moreover, it is evident that the NAE demonstrates the differences in model skill much more clearly than the RMSE, which above was termed a better discrimination between 'good' and 'bad' simulations.

To inspect the model behaviour in more detail, Fig. 4.2 displays bias and NAE separately for each season of the year, with the bias shown for both observational datasets to indicate again the observational uncertainty. It can be seen that the dominant variability among the simulations, and discrepancies with respect to observations, occur in summer and to a lesser extent in spring. For the spread among the convection schemes, this is not surprising as convective precipitation is of relatively minor importance in autumn and winter, but it is remarkable that the impact of the diffusion scheme is also maximized in summer. In fact, both the excessive rainfall in the Alpine domain and the underprediction in the Alpine foreland found in the annual mean for the σ-diffusion runs (Fig. 4.1) have their origin predominantly in summer, whereas the diffusion impact in autumn and winter is relatively small. Obviously, parameterized convection reacts much more sensitively to the diffusion-induced upslope moisture transport than grid-scale precipitation. This can be explained by a combination of two reasons. First, the trigger functions used by convection schemes are inherently sensitive to small changes of the atmospheric stability as triggering convection involves a yes-or-no decision between rainfall or not. Second, summertime convection typically occurs with weaker synoptic scale winds than frontal precipitation, so that the ratio between numerical diffusion and (physical) advection—and thus the potential for related numerical errors—is larger than in winter.

An additional view on the situation is given in Fig. 4.3 where the spatial correlation coefficients between simulations and observations are depicted for accumulated summertime rain in the total area of interest. These values essentially represent the model's ability to correctly distribute the precipitation over the area of investigation. Combined with σ-diffusion, the BM scheme again produces comparatively poor numbers whereas Grell and KF2 perform somewhat better. Interestingly, a somewhat higher correlation is found with respect to the gridded observations in the cases with σ-diffusion. This is related to the fact that the gridded dataset exhibits a relatively high maximum in the eastern central Alps that can also be found in the σ-diffusion runs. Nevertheless, a substantially better performance is found for the z-diffusion runs where the Grell- and the KF2-scheme stand out with correlation coefficients of almost up to 0.95.

As a further illustration, Fig. 4.4 displays the simulated and observed rainfall patterns for the summer season in a subdomain including the Alps and the Alpine foreland. The upper left panel shows station measurements interpolated to the 45 km grid of MM5 whereas the upper right panel depicts the gridded observational dataset upscaled to the model resolution. Note that observational data are available only for certain subregions so colours only appear in the corresponding areas. The corresponding model results for the Grell-, BM and KF2-schemes, respectively, are shown below for σ-diffusion (z-diffusion) in the left (right) column. While the observed rainfall maxima are located at some distance from the mountain tops in the upslope areas, the σ-diffusion experiments consistently exhibit their rainfall maxima near the maximum elevations of the orography, which is particularly evident in the case of the KF2-parameterization. However, the largest precipitation maxima are obtained with the BM scheme, peaking slightly south of the domain for which observational data were available. Nevertheless, it can be safely concluded that these rainfall amounts are way beyond reality as available Alpine-wide climatologies (e.g. Frei and Schär 1998) show only about half these amounts. Among the σ-diffusion runs, the Grell-scheme is closest to observations but still too much rainfall is simulated which again is too closely bound to mountain tops. Much more realistic rainfall patterns are obtained with z-diffusion, particularly when combined with the KF scheme. The Grell scheme again shows too low precipitation amounts, whereas the BM scheme still produces too much rainfall over the Alpine crest.

4.2 Performance of reference configuration of MM5

The following section is dedicated to the validation of precipitation, near surface temperature and dew point temperature of the reference experiment performed for the years of 1991 to 2000. Based on the findings of the sensitivity experiments presented above the reference simulation is performed implementing the Kain-Fritsch-2 convective parameterization together with the truly horizontal z-diffusion scheme.

4.2.1 Precipitation

Figure 4.5 shows the mean monthly values of simulated precipitation for three different subdomains of the total simulation area (cf. Fig. 3.3). Furthermore a set of error

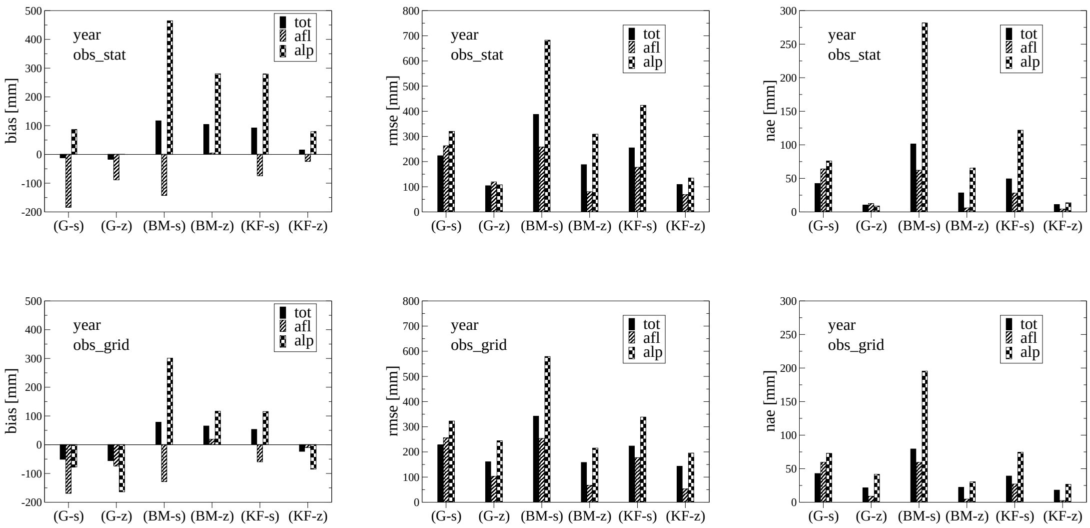


Figure 4.1: Various error measures per each subdomain ('tot', 'afl', 'alp') of simulated vs. observed accumulated rain for mean of years 1996 to 1999 as simulated with 6 different configurations of MM5. 'G', 'BM' and 'KF' stands for Grell, Betts-Miller and Kain-Fritsch-2 convective parameterization respectively, 's' and 'z' for diffusion along σ-coordinates and truly horizontal. Columns from left to right: bias, rmse and nae. Upper row with respect to interpolated station data ('obs_stat'), lower row for gridded observation fields ('obs_grid').

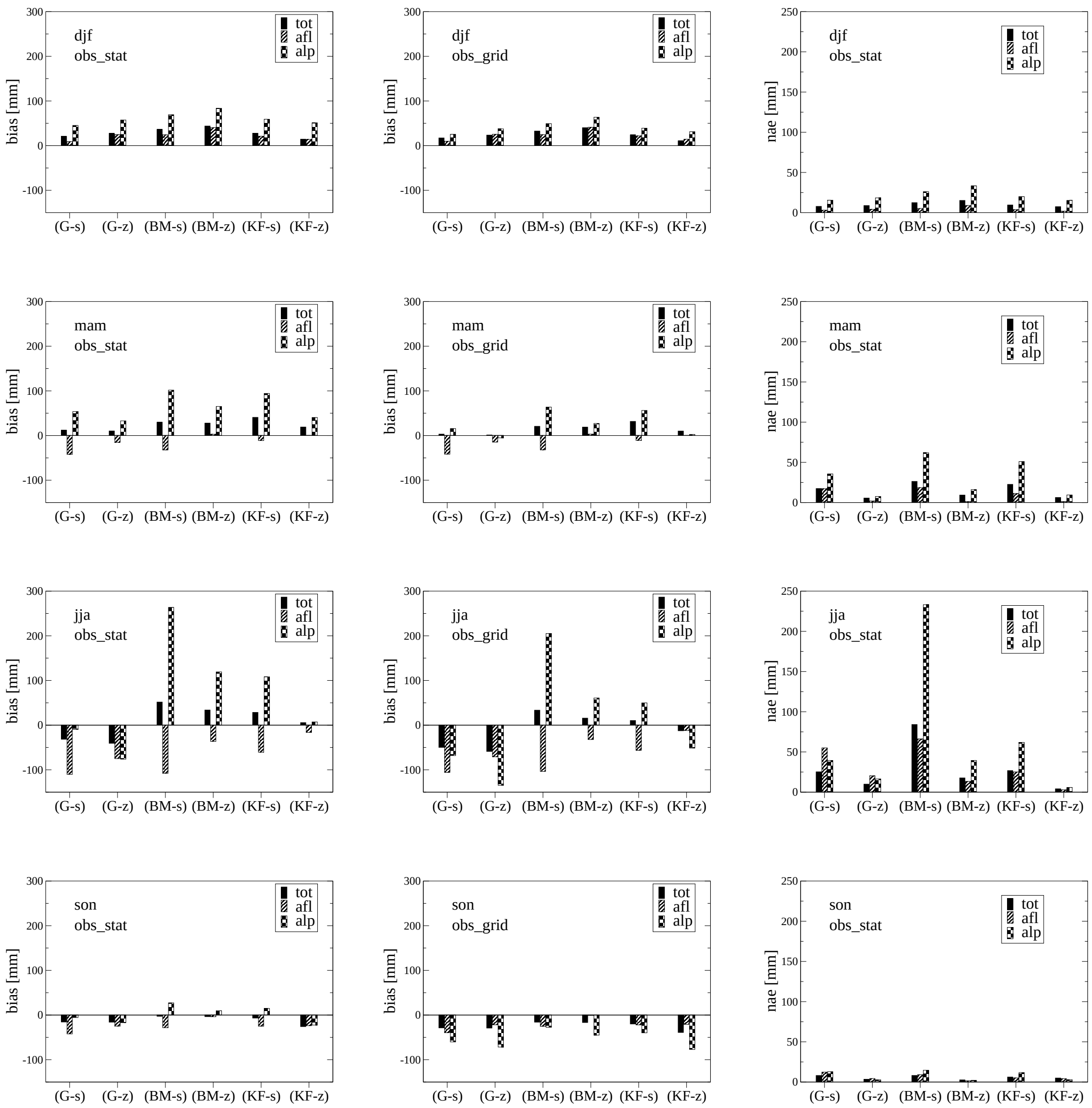


Figure 4.2: Various error analyses of simulated vs. observed accumulated rain for seasonal means of years 1996 to 1999 as simulated with 6 different configurations of MM5 (notation of runs cf. Fig. 4.1). Columns from left to right: bias with respect to interpolated station data, bias relative to gridded areal observation data and nae with respect to station data

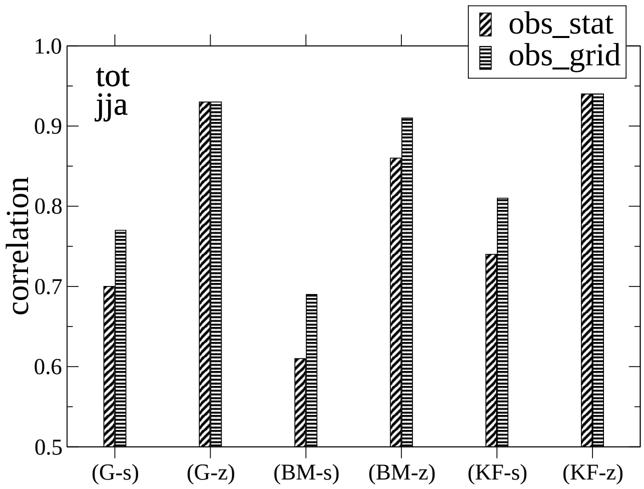


Figure 4.3: Correlation coefficients in total observation area for accumulated summertime rain of years 1996 to 1999 between observational datasets and 6 different simulations of MM5 (notation of runs cf. Fig. 4.1).

measures with respect to the two distinct observational datasets as described above is presented. For all three domains and all datasets precipitation is characterized by a rather pronounced seasonal cycle with an absolute maximum in July (Fig. 4.5a-c). Note that rainfall amounts in the Alpine area are generally somewhat larger than in the Alpine foreland or the total area, as could be expected for regions with substantially elevated orography. In the Alpine area 'obs_grid' displays noticeably more precipitation than 'obs_stat', particularly in summer and autumn, whereas in the Alpine foreland and also on average over the whole verification area the differences between both datasets are marginal.

The model is able to capture the general features like annual cycle and enhanced precipitation in elevated terrain quite well. Yet the monthly bias depicted in panels (d) and (g) reveals a tendency for underprediction in summer and overprediction in winter and spring with respect to both observational datasets. A quite peculiar feature that can be found for both datasets is the pronounced change from under- to overprediction in May when going from the Alpine foreland to the Alpine area. The apparent overprediction in the winter season might be at least to some extent due to the general problem of wind-induced underestimation in measuring solid precipitation, especially in mountainous regions (Sevruk 1985). Neither of the observational datasets apply a correction for this undercatchment. Nevertheless, the somewhat higher rainfall amounts in the gridded fields seem to reduce this discrepancy. Yet still there remains an obvious tendency to underprediction of summertime rain particularly in the Alps, which suggests a deficiency in the cumulus convection scheme. One possible factor might be that the cumulus scheme does not account for the effects of unresolved subgrid scale orography.

According to the RMSE shown in Fig. 4.5(e,h), the simulation shows rather uniform

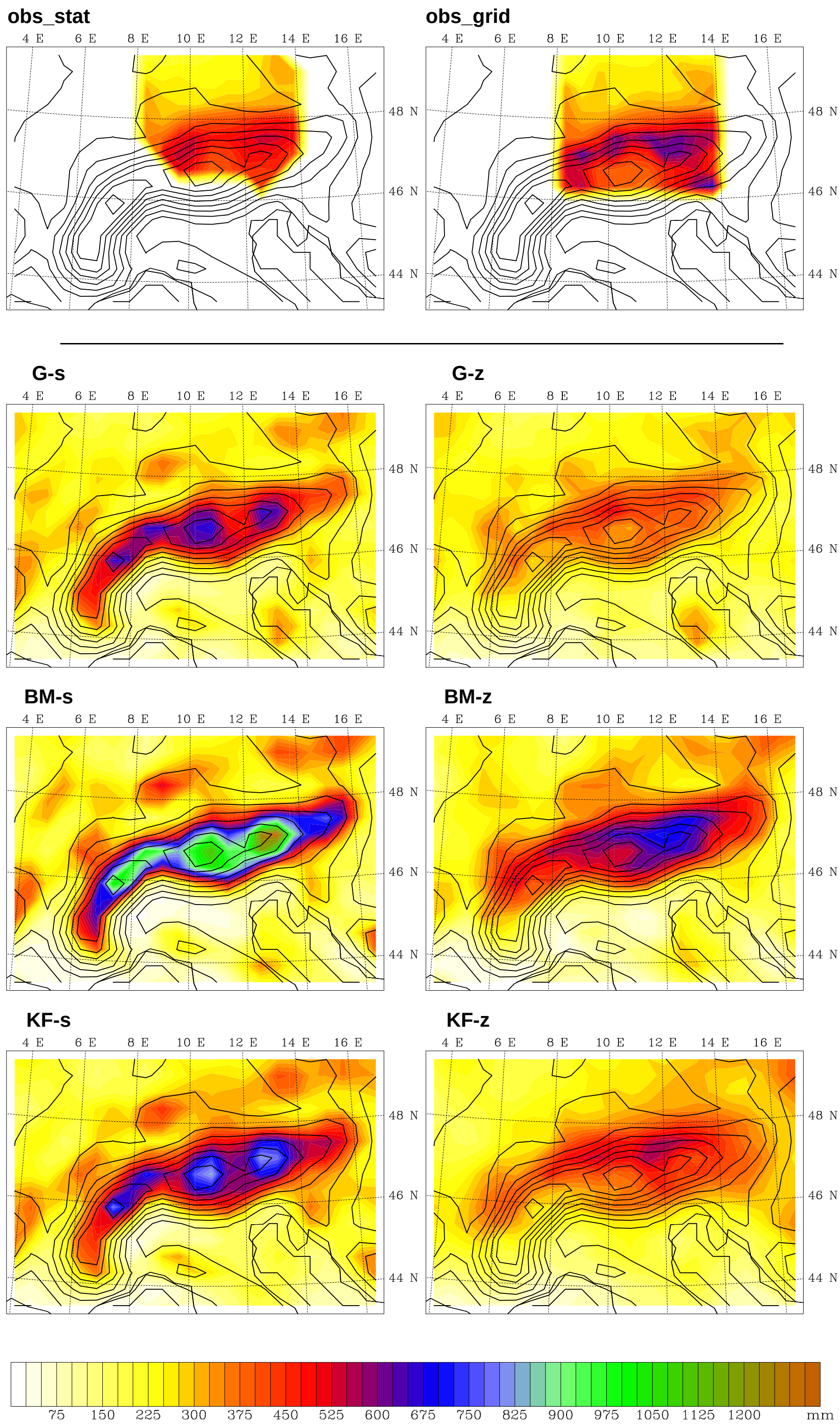


Figure 4.4: Observed and simulated rain for summer (JJA, mean of 1996–1999). Upper row spatial averages of station data ('obs_stat') and gridded dataset ('obs_grid') (see text). Lower rows simulations with three different convection schemes (Grell, Betts-Miller, Kain-Fritsch-2): left column with σ-diffusion, right column with truly horizontal diffusion (notation of runs cf. Fig. 4.1). Isolines indicating model orography.

deficiencies throughout the year, whereas the NAE (Fig. 4.5(f,i)) reveals much more variability between individual months of the year. This in turn allows for a more differentiated assessment of the model performance in view of the two observational datasets. For example, the NAE indicates the largest discrepancies with respect to the averaged station data in winter and spring but in July and September with respect to the gridded dataset.

Figure 4.5 generally indicates the largest model deficiencies in the Alpine region, especially when referring to the gridded dataset. This is not unexpected because the Alpine topography is very poorly resolved at a mesh size of 45 km, implying that the complex orographic influences on rainfall generation cannot be captured accurately by the model. However, the comparatively high observational uncertainty also reflects problems of the validation itself. Note that the average simulated rainfall amounts in the Alpine domain (Fig. 4.5c) still range between the two observational data sets in 4 out of 12 months and are clearly outside the range of uncertainty in January, July and September only. The sensitivity experiments presented in the previous section demonstrate that this level of model skill is by no means easy to achieve.

4.2.2 Near surface temperature and dew point temperature

Observed versus simulated near surface temperatures are presented in Fig. 4.6. Shown in each graph is the mean diurnal cycle of temperature for each month of the year. All in all there is quite a good correspondence between simulation and observations. In summer when near surface temperature is predominantly determined by the incoming solar radiation, the timing of the temperature increase and its slope in the morning are simulated almost perfectly by the model. The slight timeshift of about 15 minutes between model and observations can mostly be attributed to the practice of observers to perform their measurements about 10 minutes before the full hour (although the values are labeled with the full hour). It should be mentioned here that the radiation scheme of MM5 is called every 20 minutes, and the value of the solar inclination angle used for the calculations is centred in time for this period. Thus, the way of calculating radiation should not significantly contribute to the time shift. In the afternoon hours, however, a bias of up to -2 K has to be stated that gets reflected in a general timeshift in the maximum temperature of about 1 hour in the simulation. Note that a similar finding is reported e.g. by Hohenegger et al. (2008) for CLM. The possible reasons for this behaviour are manifold. For example, one seemingly obvious explanation would be that the PBL-scheme imposes somewhat too strong mixing that transports too much heat away from lower parts of the atmosphere. Strong mixing could also lead to excessive drying of the near surface atmosphere, leading to more evaporation from the soil and eventually to an altered bowen ratio, so that a too small fraction of the solar radiation absorbed by the underlying soil is transformed into sensible heat. However, the notion of too intense mixing is not supported by the dew point temper-

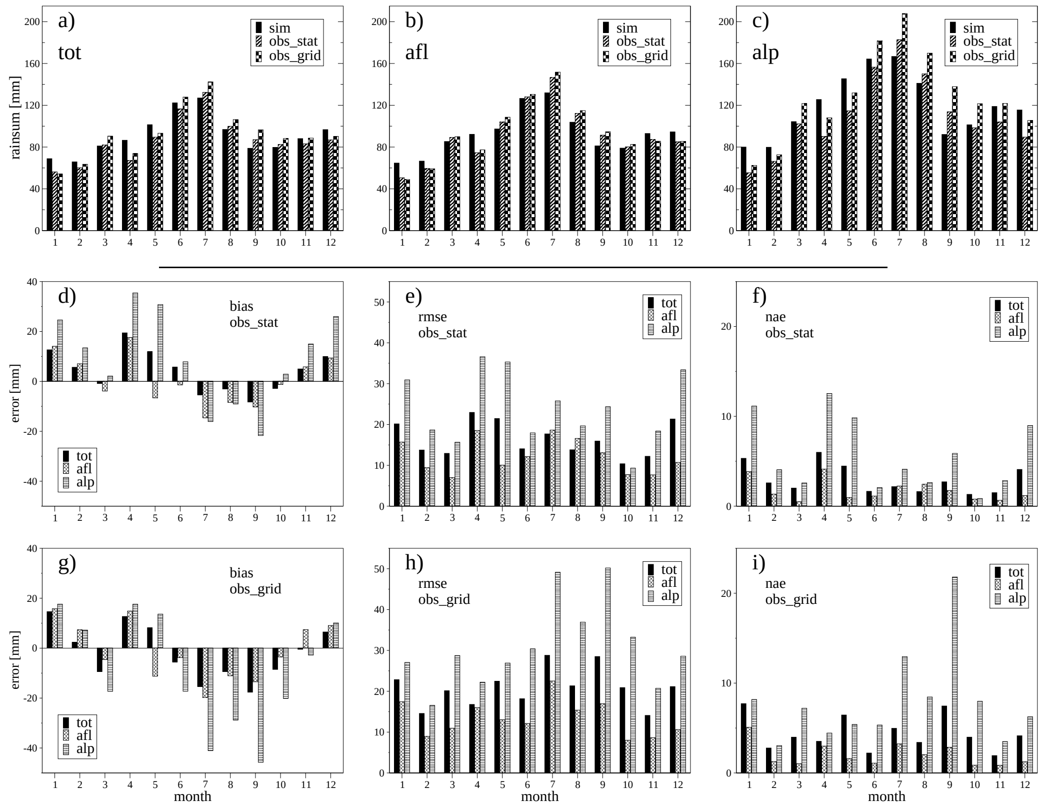


Figure 4.5: Upper row: accumulated monthly rain for years 1991 to 2000 simulated by MM5 ('sim'), averaged from station data ('obs_stat') and from aggregated high-resolution fields ('obs_grid') for total validation area ('tot'), Alpine foreland ('afl') and Alpine area ('alp') respectively. For areas see also Fig. 3.3. Second row gives values in subdomains for 'bias', 'rmse' and 'nae' in relation to averaged station data; third row shows corresponding values referring to gridded observational fields.

ature validation (see below). A similar error in the bowen ratio could also be related to the formulation of the evaporation from plants and soil, or simply to the vegetation fractions and soil types assumed in the model. Cooley et al. (2005), for example, perform simulation experiments with MM5 and a coupled landsurface module including effects of harvesting on regional climate. Here, the removal of evaporating plants, i.e. changing the vegetation fractions, has significant effects on the bowen ratio and the near surface temperature. Furthermore, inaccuracies in the calculation of downward longwave radiation might contribute to the temperature bias observed. Fernandez et al. (2007), however, do not find substantial differences in simulated 2-m temperature for MM5 simulations over the Iberian Peninsula resorting to a more sophisticated (and computationally more costly) longwave radiation scheme in comparison to the respective parameterization used for the present study. Last but not least, the formation of clouds in the afternoon may exert a substantial influence on near surface temperature (Hohenegger et al. 2008). Yet further investigations on these issues are beyond the scope of the present work and should be addressed in future studies, focusing also e.g. on different formulations of the PBL. The overall features of the observed and simulated diurnal temperature cycle in July prove to be more or less representative for all months of the year (Fig. 4.6). Even in winter the behaviour does not change substantially as could have been expected from the fact that the near-surface temperature then is less strongly controlled by the incoming solar radiation, and advection or large scale forcing has a relatively larger influence compared to local processes (Chen et al. 2003). Nevertheless, observed and simulated temperatures are still in rather good agreement, and the timing of the temperature rise in the morning is well captured by the model again. Evaporation from soil or even plants will, of course, have a small impact in winter. However, the formulation of ground and soil heat fluxes might be relevant in winter (Chen et al. 1997). In particular, the existence and extent of snow cover is crucial for modelling of the wintertime near surface temperature (Zhang 2005). More detailed month-by-month analyses (not shown) also revealed that the largest biases occur in months with persistent low stratus conditions, suggesting deficiencies in the ability of the model to simulate stratus clouds to a realistic extent. This could, for example, be related to deficits in the cloud-radiation interaction (Guan et al. 2000) or to unrealistic drizzle formation by the microphysics scheme (Lynn et al. 2005).

To shed some light on the simulated moisture budget in the lower atmosphere, Fig. 4.7 shows the mean diurnal cycle of the 2-m dew point temperature for each month of the year. In summer the correspondence between model and measurements at nighttime and in the early morning is again quite good. The onset of early morning evaporation at sunrise and the amount of released water vapor seem to be simulated quite realistically. Also, nighttime formation of dew obviously is captured very well. After 8 UTC in the morning, however, when the observed dew point temperature decreases and finally forms its ideal bimodal diurnal wave, the simulation follows a substantially different path. Hohenegger et al. (2008) also found pronounced overprediction of near surface humidity in July especially in the afternoon hours. This behaviour of the simulated dew point temperature strongly suggests that the PBL scheme produces not enough vertical mixing, which in reality transports drier air from above towards the surface to build the well known bimodal diurnal structure of the 2-m dewpoint.

This finding also reduces the number of possible reasons for the deficits of the near surface temperature discussed above. The speculations on too intense mixing in the PBL can be ruled out most likely. The cold bias of air temperature together with a positive bias in air humidity rather suggests too intense evaporation from the soil as the most likely reason. Maybe some very fundamental approaches like e.g. the Monin-Obukov-hypothesis (Stull 1988, Garratt 1994) for mixing found in a great variety of models also require further adaptions and improvements. The characteristics in July are more or less typical for all months of the warmer seasons. In winter, when mixing in the PBL is generally rather weak and also no bimodal diurnal cycle in dew point temperature is observed, the shape of the simulated curves is rather similar to the measured ones but with a midday (moist) bias of up to 2 K.

4.3 Summary and Discussion

The sensitivity experiments presented in the first section of the current chapter clearly revealed the considerable differences in the simulation of precipitation depending on the convection parameterization used. Somewhat surprisingly, also the formulation of the horizontal diffusion exerted a large influence on generated rain with a similar order of magnitude. For the comparatively coarse resolution of 45 km, and thus only moderately steep gradients of the model orography, the terrain following 'horizontal' transport of moisture was not expected to exert such a remarkable effect.

Computing horizontal diffusion along terrain following σ-coordinates inevitably entails a systematic vertical transport over sloping terrain. In the case of moisture (i.e. water vapour mixing ratio), which in nature typically tends to decrease exponentially with height, this leads to an unphysical transport of water vapour from the foothill areas to the mountain tops. This destabilizes the atmospheric stratification and facilitates the development of convection with particularly notable impact on the model results in the case of parameterized convection. This effect has already been suspected as a possible reason for excessive simulated precipitation amounts by Simmons (1986) and Giorgi (1991). Simmons suggests either to apply horizontal diffusion to variables that are much more uniformly distributed in the vertical, if possible, or to introduce correction terms within the diffusion scheme, relying on reference profiles for the respective variables, in order to apply horizontal diffusion in a 'more truly horizontal plane'. The most straightforward approach to avoid these effects, however, is to constrain the numerical diffusion scheme a priori to a truly horizontal transport which is achieved by the truly horizontal 'z'-diffusion scheme implemented by Zängl into the MM5 (2002).

The sensitivity experiments of this dissertation thus for the first time draw a con-

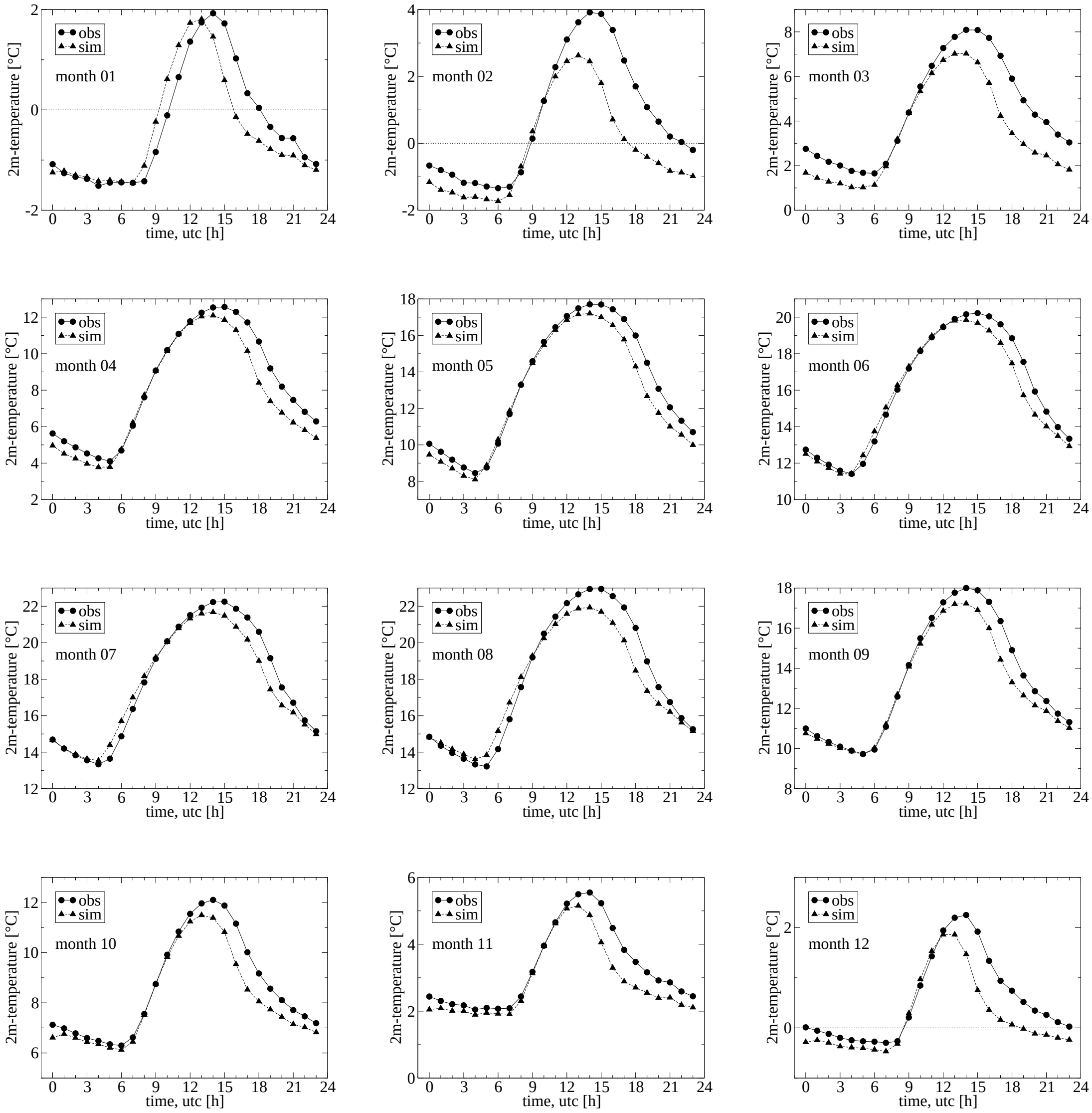


Figure 4.6: Observed ('obs') and simulated ('sim') mean diurnal cycle of near surface temperature for individual months (mean for years 1991 to 2000).

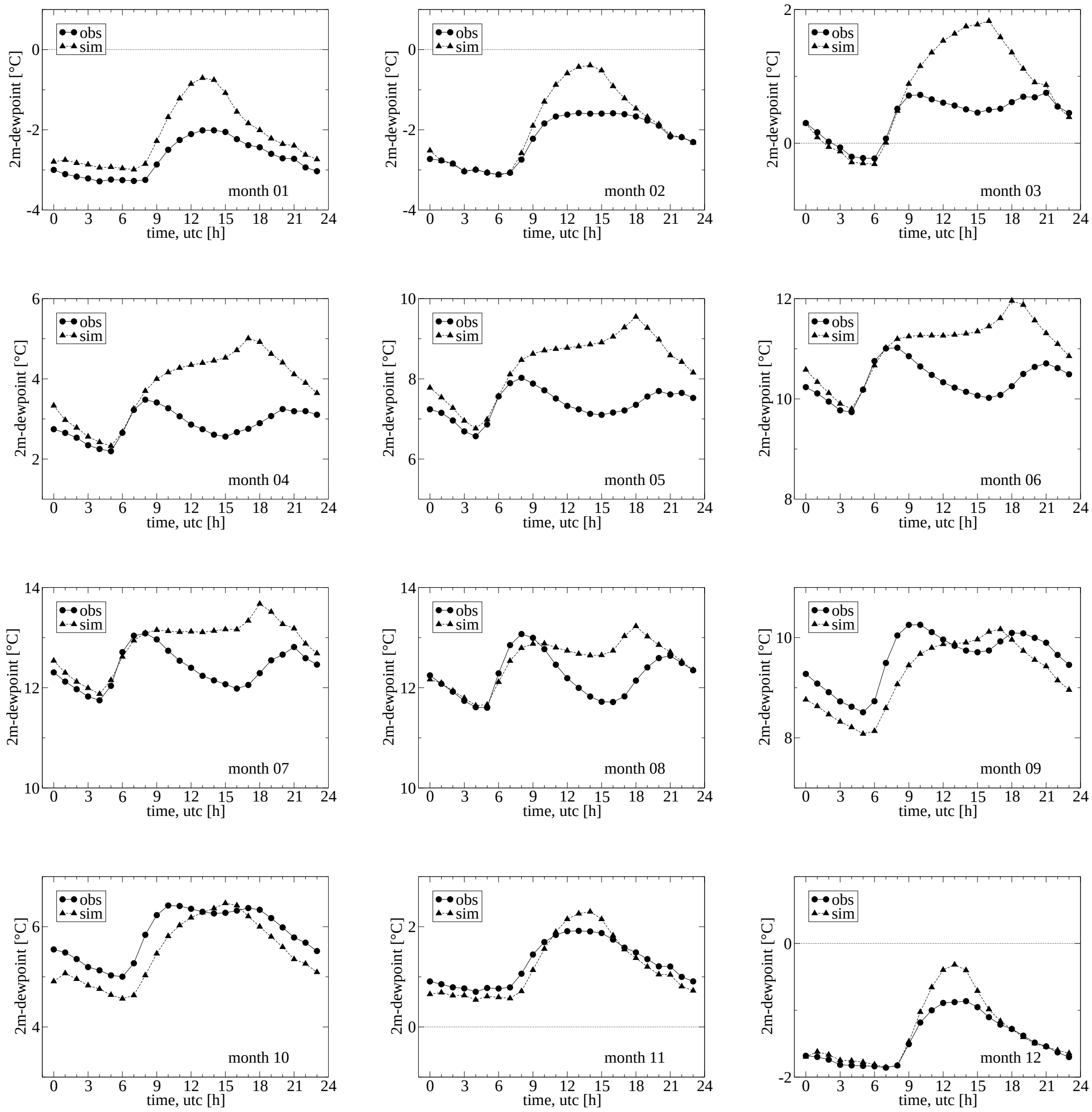


Figure 4.7: As Fig. 4.6 but for near surface dew point temperature

clusive comparison of the dramatic effects of the σ- vs. the truly horizontal 'z'-diffusion scheme on simulated precipitation in mountainous terrain in the context of regional climate modelling.

The MM5 all in all proved to be the ideal testing environment due to the ease of exchangeability of physics routines it offers. The worst combination of both options in the context of this study, i.e. the Betts-Miller scheme together with σ-diffusion, resulted in a dramatic overprediction in the higher Alpine area, particularly, in summer. Even with truly horizontal diffusion the Betts-Miller scheme already showed substantial surplus precipitation. The unphysical supply with extra moisture provoked by the terrain-following diffusion aggravates this behaviour impressively. This is also true, to a little less but still noticeable extent, for the other convection schemes. The misallocation of precipitation between the Alpine foreland, where moisture gets transported away, and the higher Alpine area with its surplus rainfall amounts also gets reflected in the corresponding areal correlation coefficients. The normalized absolute error, introduced in the previous chapter, allows for a much clearer assessment of the performance of the various model configurations compared to the RMSE. Whereas in the 'RMSE view' several simulations seem to be fairly similar in their performance the NAE quite distinctly names the outliers and the 'winners'. Only the combination of both, the appropriate convection scheme, i.e. the Kain-Fritsch-2 scheme, and the truly horizontal diffusion, allowed for quite realistic simulations of precipitation in all aspects, i.e. with total seasonal amounts as well as patterns falling in the range of observational uncertanties.

In the second section, the extension to a simulation period of a whole decade, performed with the reference configuration as identified in the first section, corroborates the findings with respect to precipitation. The annual cycle of mean monthly precipitation amounts is reproduced fairly well in the Alpine foreland as well as in the Alpine area with a characteristic pronounced maximum in July. Noticeably more precipitation naturally is observed as well as simulated in the more elevated area. Capturing realistic precipitation amounts, both by observations and in modelling, obviously is more demanding in mountainous areas. This gets reflected here in the somewhat more distinct discrepancies between the three datasets considered. Beyond precipitation also another very important variable in climate studies must not be lost sight of, i.e. near surface temperature. Thus, simulated mean diurnal cycles of the 2-m temperature were compared to observed data showing very good correspondence. Only in the afternoon hours a systematic cold bias occurs that also is found for other comparable models (e.g. Hohenegger et al. 2008). Additionally, also information on near surface moisture in the form of the mean monthly diurnal cycles of the 2-m dew point temperature was analyzed. Here, somewhat more substantial discrepancies to observations can be found. Whereas nighttime and early morning values are captured very well, the shape of the curves differ quite evidently in the afternoon, as was similarly reported also by Hohenegger et al. (2008). The cold bias connected with the surplus afternoon moisture could very well be due to too much evapotranspiration. This possibly could be traced down to inaccuracies in the landsurface/vegetation scheme. The cold bias also might be induced by a surface radiation budget that is perturbed by unrealistic cloud formation, that itself is a complex process governed by the moist physics scheme and its manifold feedbacks to various variables. The fact that a similar behaviour of both near surface variables occurs in different models also might suggest that a very basic problem exists in approaches common to many models, such as the similarity theory applied in the calculation of surface fluxes (Stull 1988, Garrat 1994). Thus, some possible starting-points suggest themselves here for some future, partially very fundamental research, that however goes beyond the scope of the current study.

All in all, however, the first goal of this study, i.e. to identify the proper configuration of MM5, most appropriate for the purposes of GLOWA-Danube, with highly realistic simulations of the key-variables precipitation and near surface temperature, has been achieved successfully.[1]

[1]The findings of this chapter are also presented in Pfeiffer and Zängl 2010

Chapter 5

Validation of MM5 simulations driven by ECHAM5

The optimal configuration of MM5, i.e. the combination of physics parameterizations, with emphasis primarily on precipitation in Southern Germany and the Northern Alps, has been identified and validated in the previous chapter. The present chapter is dedicated to the second step of the validation of the nested model approach, i.e. the analysis of the impact of different driving input data onto the regional simulation. Thus, an intercomparison of long-time MM5 simulations driven by 'observational' data against GCM output will be given.

Boundary data for the years 1971-2000 are either taken from ECMWF's ERA40 reanalysis project or from a transient ECHAM5 simulation (with prescribed greenhous gas concentrations as observed for this period) as conducted for the fourth IPCC assessment report with resolution T63L31 coupled to the ocean model MPI-OM GR1.5L40 (cf. Roeckner et al. 2003).

The evaluation and assessment of the results will have its focus on the Alpine region and here especially on the elevated areas above 1000m in the north and south of the eastern part of the Alpine crest. The corresponding areas are depicted in figure 5.1.

5.1 Seasonal patterns and annual cycle of precipitation

Exchanging the driving GCM ideally should not bring about substantial consequences on the climatological characteristics of precipitation in the MM5 simulations. Yet the effects are quite considerable as can be seen in Fig. 5.2. In the left (middle) column, the mean seasonal accumulated precipitation is shown for each season in the greater Alpine region for MM5 simulations driven by ERA40 (ECHAM5). The right column depicts the corresponding relative over- or underprediction for simulations driven by ECHAM5. The seasonal patterns simulated by MM5-ERA40 resemble quite well in their general features to e.g. the elaborate observational climatology of precipitation for the Alpine region by Frei and Schär (1998). Highest overall precipitation amounts over land are

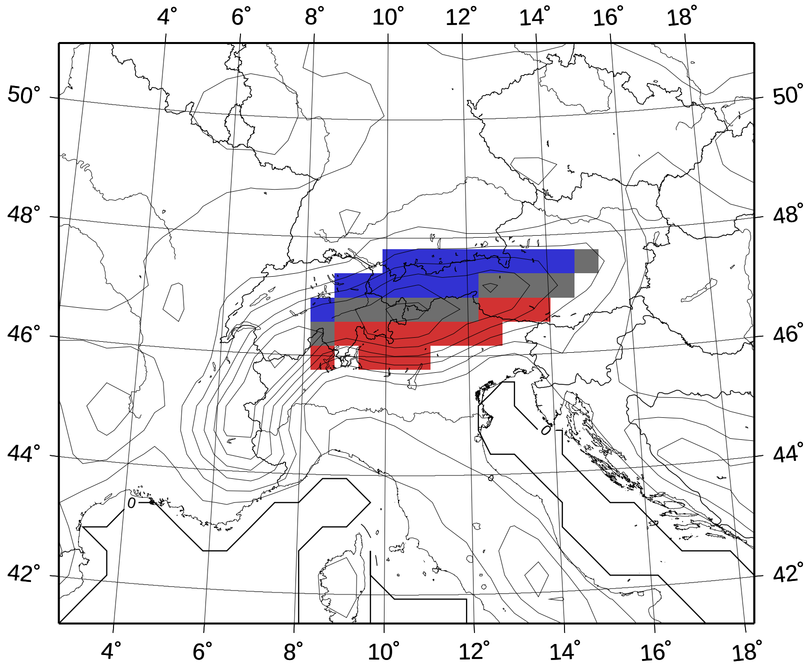


Figure 5.1: Subdomains defined as N-Alp (blue) and S-Alp (red), both together with Alpine crest as T-Alp (blue+red+gray). The whole domain shown here will be referred to as 'greater' Alpine region G-Alp.

observed and simulated in summer in the northern Alpine area and contrasted by a rather dry south-western part of the Alpine arc. Winter is generally much drier with the main maximum shifted to the north-western area of the Alpine arc. Spring and autumn fall in between the other two seasons with respect to precipitation and show similar patterns with two moderate maxima located in the north-west and south-east of the Alpine arc whereas in spring somewhat more precipitation is found in the northern Alpine region in the simulation. The distinct gradient in precipitation between the Alpine foreland and the northern Alps also corresponds well with observations analyzed in detail e.g. by Wastl and Zängl (2007).

Replacing the observation-based global dataset ERA40 with ECHAM5 data entails a noticeable change of precipitation amounts in the Alpine domain. This is particularly true in the colder seasons. Also for Italy a substantial overprediction with a factor of more than 2 gets obvious close to the western slope of the Apennine Mountains with a corresponding decrease of rainfall in the east—a response indicating more wind from westerly directions at the expense of easterly winds when switching to ECHAM5. In the following, however, the analysis will be concentrated on the Alpine area. The over-prediction here reaches an overall amount of up to 80 % in winter. Weaker surplus precipitation extends over the whole north and west of the greater Alpine area. This suggests that the ECHAM5 generated climate involves too many cyclone passages, apparently combined with too high cyclone intensities, which leads to excessive orographic precipitation enhancement over the Alpine slopes. The situation in autumn resembles that of winter but with somewhat less overprediction. The least overall differences between both simulations are found for spring. In summer a remarkable underprediction appears south of the Alps and over most of the Mediterranean part of the analysis domain. In the area of the northern Alps and in the Alpine foreland no remarkable differences can be found.

Figure 5.3 on the one hand summarizes the findings so far by building areal averages of precipitation for the regions of interest, i.e. the higher Alpine regions north and south of the Alpine crest and the greater Alpine area as defined in figure 5.1. On the other hand it refines the temporal resolution by going from mean seasonal to mean monthly values in their annual cycle. On the left results of MM5-ERA40 simulations are presented showing again good agreement with observed mean annual cycles of corresponding domains as analyzed in detail again e.g. by Frei and Schär (1998). Naturally, highest precipitation amounts are found in the higher Alpine regions (orographic enhancement!) and here, due to the predominant westerly to north-westerly winds, in the northern parts (N-Alp) except for the month of October. A distinct maximum in summer (i.e. June) stands out against lowest precipitation (depending on the domain under consideration) in February or September. In contrast, for MM5-ECHAM5 the annual cycle shows a second pronounced maximum for winter that seems to lie outside the range of observations (cf. e.g. Frei and Schär 1998, Pfeiffer and Zängl 2010). Summer and spring, on the other hand, seem to be reproduced quite realistically, whilst autumn already shows some tendency to overprediction. All in all the annual cycle of mean monthly precipitation confirms the findings gathered from the precipitation patterns.

5.2 Analysis of large scale circulation

The markedly altered precipitation patterns and rainfall amounts revealed substantial deficiencies of the ECHAM5-driven simulation especially in mountainous areas where rainfall generation is strongly influenced by orographic lifting. This suggested a closer analysis of the large scale circulation in the simulation area depending on the driving GCM. Figure 5.4 juxtaposes the seasonal mean sea level pressure for the years 1971 to 2000 simulated by MM5 driven with ERA40 and ECHAM5 data, respectively. Differences mainly get obvious in winter and autumn. In winter for both cases lowest pressure values a little below 1000 hPa are found over the Atlantic ocean. The extended area of low pressure seems to be shifted a little to the south under ECHAM5 compared to the situation with ERA40 input. Important to note is also the corresponding change in the general flow direction especially in the Alpine region. Whereas with ERA40 the mean isobars show a south-westerly component there, this pattern changes to a mainly westerly orientation under ECHAM5.

Another remarkable feature is the lower pressure over south-eastern Europe with

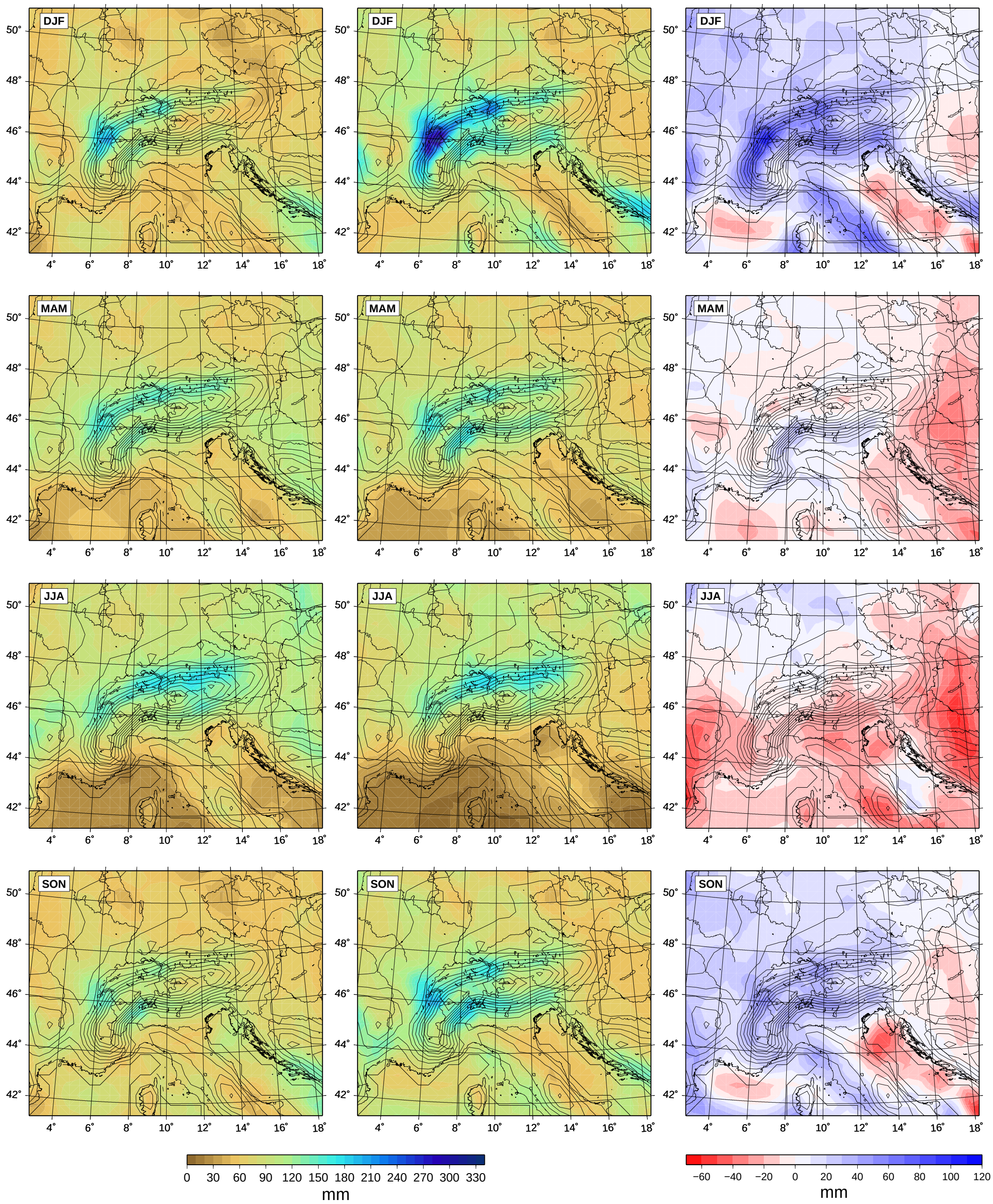


Figure 5.2: Seasonal mean precipitation (1971-2000) simulated by MM5 driven by ERA40 (left), driven by ECHAM5 (middle), and over-/underprediction driven by ECHAM5 compared to ERA40 (right) in the greater Alpine area G-Alp

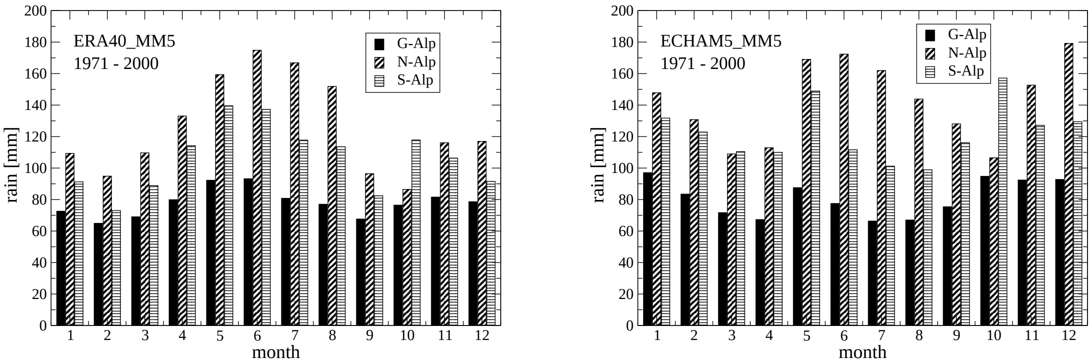


Figure 5.3: Mean monthly precipitation simulated by MM5 driven by ERA40 and ECHAM5 for the greater Alpine area (G-Alp) and for northern (N-Alp) and southern Alpine (S-Alp) grid boxes as defined in figure 5.1

a difference of up to 10 hPa. This is accompanied by a 'compensatory' rise of sea level pressure in the western Mediterranean and over Spain. In autumn the structural differences are similar but less pronounced whereas in spring and summer the changes of the overall pattern are comparatively marginal. It should be mentioned here that such deviations in the large scale flow over Europe are not an exclusive feature of ECHAM5. Buonomo et al. (2007), for example, also find comparably large differences in the mean sea level pressure between ERA40 and the HadCM2 global circulation model.

Further consequences of the altered pressure fields in the Alpine area are presented in figure 5.5 in the form of seasonal mean wind speeds at the pressure level of 700 hPa that (at the given model resolution) lies slightly above the highest mountain tops. On the left (right) results of MM5 simulations driven by ERA40 (ECHAM5) are shown. In the Mediterranean area generally lower wind speeds are generated than north of the Alps for all seasons. The colder seasons are characterised by higher wind speeds in accordance with higher gradients of sea level pressure (cf. Fig. 5.4). The overall rise of wind speeds for simulations driven by ECHAM5 is quite remarkable, particularly over the central Alps, where mean(!) wind speeds in winter reach values of about 16 m/s compared to 12 m/s for MM5-ERA40.

Besides wind speed also wind direction statistics are important for understanding precipitation differences in the Alpine region, as intensified flow parallel to the Alps will have much less influence on rain generation than stronger wind hitting the Alps orthogonally. Figure 5.6 accordingly aggregates information about the occurrence of different wind speed classes and their allocation to different wind direction bins in the central Alps (i.e. terrain heights above 1000m in the model's orography; cf. domain T-Alp as defined in fig. 5.1). Three-hourly data simulated by MM5 (left ERA40, right ECHAM5) were evaluated again at the 700 hPa pressure level. Events with wind speeds below 5 m/s are not classified. At first sight a pronounced maximum for westerly wind directions in any season gets obvious for both cases. A minimum can be found for easterly wind. The maximum for westerly directions complies with the mean pressure fields (Fig. 5.4). Switching input from ERA40 to ECHAM5 a clear tendency towards higher wind speeds has to be stated in all seasons for almost all wind direction classes. This also gets reflected in the decreasing weak wind counts. Specifically a distinct shift to higher wind speeds gets obvious for westerly and north-westerly directions, which is consistent with the enhanced pressure gradients showing up in the seasonal means displayed in figure 5.4. In summer the most pronounced decline in events with 'zero-' and low windspeed is found for all seasons.

5.3 Relationship large scale flow — precipitation

Figure 5.6 provides statistics of simulated wind speeds and wind directions in the higher Alpine area that are valid for both subareas N-Alp and S-Alp (cf. Fig. 5.1) at the height of consideration, i.e. 700 hPa. A corresponding analysis of precipitation where rainfall amounts are partitioned to different wind speed and wind direction classes in contrast has to be compiled separately for these two domains—distinct differences have to be expected due to the different exposure of the orography to the flow north and south of the Alpine crest. This becomes obvious in figures 5.7 and 5.8 where the fractions of the total seasonal precipitation of each wind speed class (in steps of 5 m/s) are depicted against the respective wind direction separately for the area north and south of the Alpine crest. The absolute mean monthly precipitation amounts for both regions can be taken from figure 5.3 for reference. In winter MM5-ERA40 simulates in area N-Alp most precipitation for the higher wind speed classes from north-westerly and adjacent directions in accordance with observations (cf. Wastl and Zängl 2007, 2008). MM5-ECHAM5 dramatically overweighs this fraction. Obviously, the higher wind speeds from the appropriate direction—providing sufficient supply of moisture from the Atlantic—lead to excessive generation of precipitation due to rapid orograhic lifting. In autumn MM5-ERA40 rainfall is somewhat more evenly distributed between northerly and westerly directions and different wind speed classes compared to the situation in winter. Even a non-negligible contribution by southerly flow can be noticed for the lower wind speed classes. Switching to ECHAM5 input the distribution again resembles that of winter, yet not as pronounced, with a dominant influence of north-westerly intense winds. The situation in spring in turn resembles that of autumn but the higher importance of low wind speed events from westerly directions can still be found for MM5-ECHAM5, only slightly beaten again by north-westerly winds with moderate wind speeds. Summer finally is characterised by distinctly more precipitation related to very low (below 5 m/s), low and moderate wind speeds coming from westerly directions. With ECHAM5, however, while basically preserving the shape of the distribution, higher wind speeds are again overweighed in respect to their role in rainfall generation.

The picture for the region south of the Alpine crest (cf. Fig. 5.8) differs, as expected,

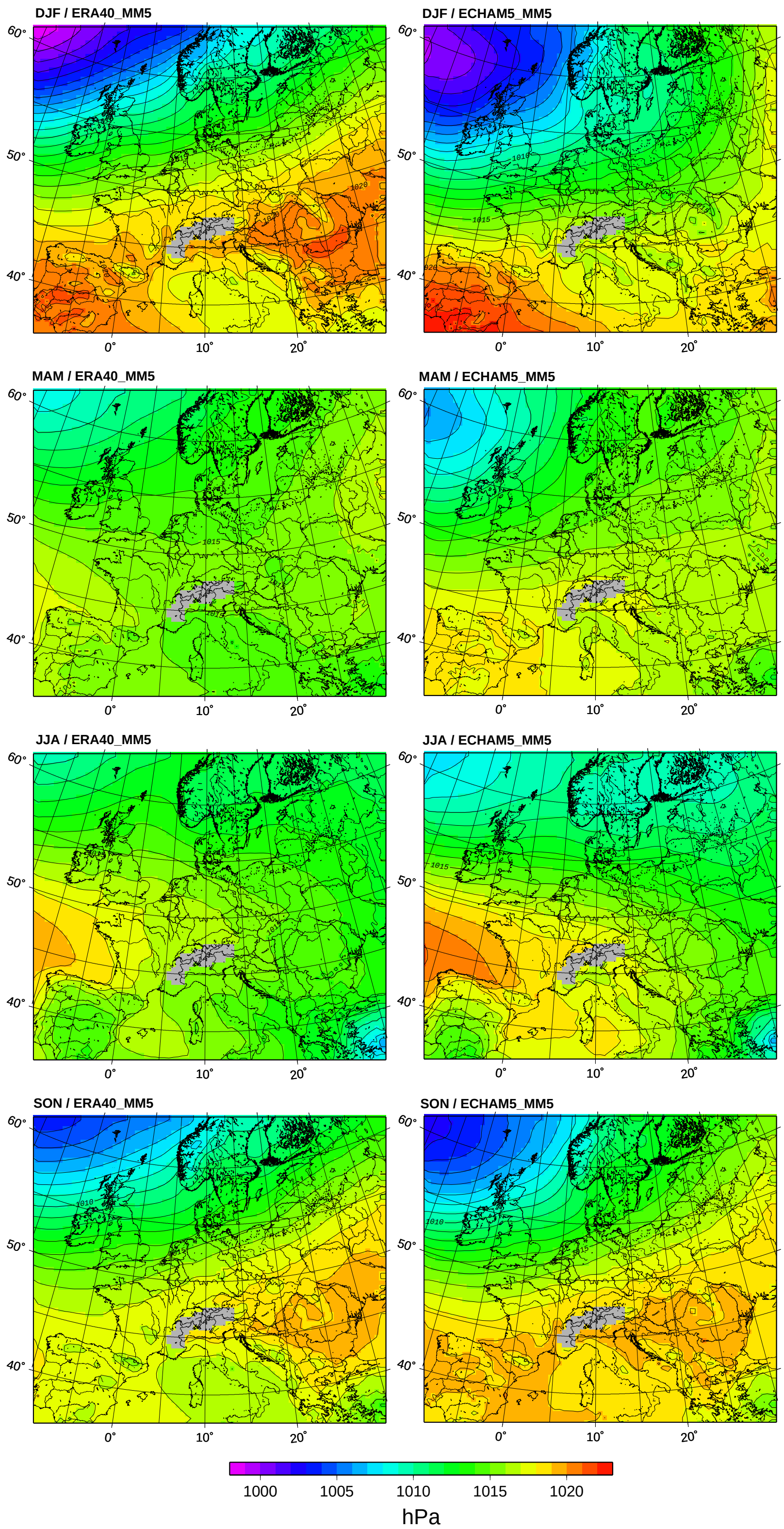


Figure 5.4: Seasonal mean sea level pressure (1971–2000) simulated by MM5 driven by ERA40 (left) and ECHAM5 (right) in total model domain. The higher (above 1000m) Alpine area has been masked to avoid unrealistic results of pressure reduction to sea level

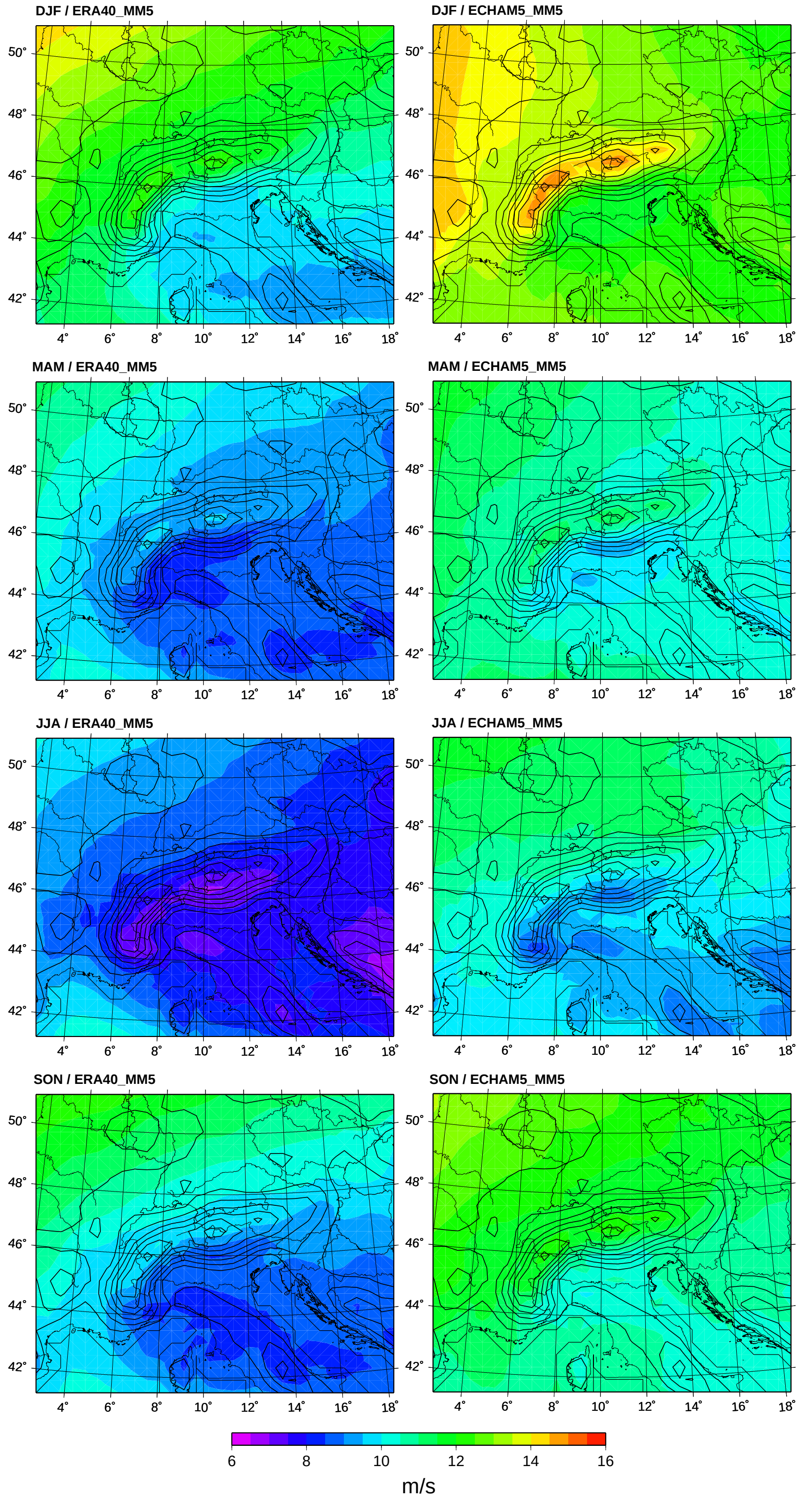


Figure 5.5: Seasonal mean wind speed (1971-2000) at 700 hPa simulated by MM5 driven by ERA40 (left) and ECHAM5 (right) in greater Alpine area G-Alp

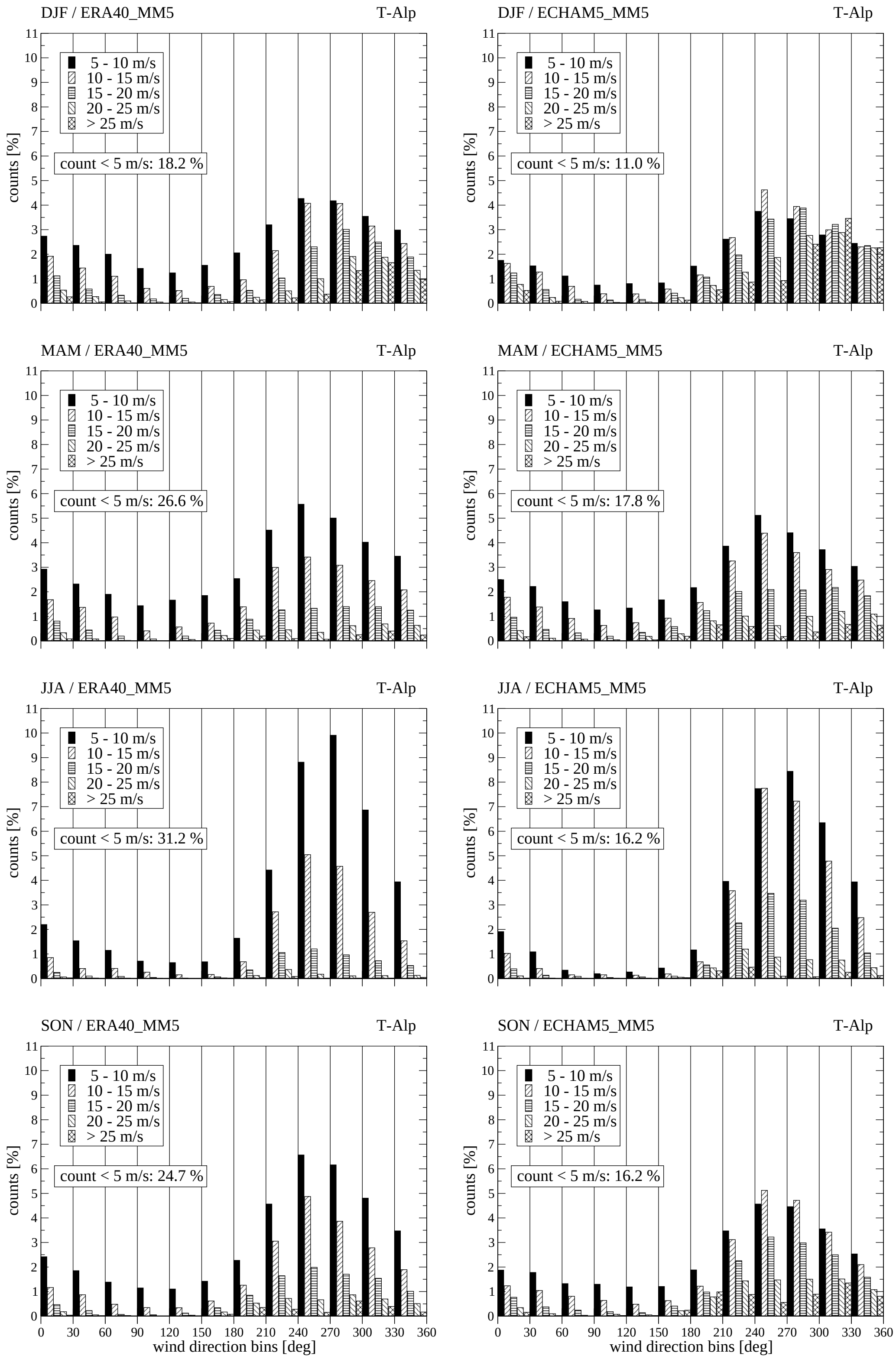


Figure 5.6: Relative occurrences ('counts') of wind directions (1971–2000, three-hourly data) for several wind speed classes at 700 hPa in total Alpine area T-Alp (cf. Fig. 5.1) simulated by MM5-ERA40 (left) and MM5-ECHAM5 (right) for each season. Relative counts in each panel sum up to 100%

remarkably from that for N-Alp mainly for the colder seasons. For MM5-ERA40, the predominant maximum of simulated winter precipitation shifts from north-westerly to south-westerly directions and towards somewhat lower wind speeds. This does not change essentially for MM5-ECHAM5, but higher wind speeds still get overweighed, which is also generally true for autumn and spring. In summer finally only minor differences could be found with respect to MM5-ERA40 for both regions, which could be expected due to the dominant west-southwesterly moderate flow oriented parallel to the Alpine crest (cf. Fig. 5.6) that is also equally responsible for the major portion of precipitation north and south of the crest. With ECHAM5 the wind statistics change mainly towards higher wind speeds from south-west with the most noticeable decrease in events with lowest windspeeds (below 5 m/s) from about 33.7 to 18.7 %.

A final look at the simulated precipitation under the two global climatologies is given in figure 5.9 from a different point of view. Here the relative portions of 3-hourly precipitation amounts (binned in steps of 0.2 mm) to the accumulated precipitation in the central Alpine area T-Alp are depicted for each season. For approximate actual values of total rain refer to figure 5.3 (monthly precipitation in subdomains N-Alp and S-Alp). The highest contribution of up to 11 % in winter is accounted for by events with light precipitation with a peak for 3-hourly mean rainfall rates of around 0.4-0.6 mm. In summer the curve is substantially broadened and the actual maximum seems to be shifted to a value of around 1 mm/3 hours indicating a much larger variability with more vigorous precipitation events represented by the long tail towards higher precipitation rates. Whereas the most narrow curve naturally is found for winter the distribution for spring already gets slightly broader. Autumn shows similar structures as summer. The major differences between MM5-ERA40 and MM5-ECHAM5 again can be found for winter and to a smaller extent for autumn. The relative contribution of light precipitation events to the total amount is discernably reduced in favour of higher classes. The general shape of the curves however is preserved and follows a gamma distribution that is obviously common to precipitation spectra (observed or reasonably simulated) of any season and any climate as has been investigated by e.g. Zolina et al. (2004) and Gutowski et al. (2007). Spring and summer on the other hand do not show any clear shift in their precipitation spectra. Note, that changes or inaccuracies in the intensity distribution—even for unaltered total precipitation amounts—can entail massive effects in subsequent climate impact studies e.g. in the field of flood prediction.

5.4 Summary and Discussion

MM5 simulations (with the optimized configuration discussed in the previous chapter) driven by 30 years (1971–2000) of the observation based ERA40 data feature quite realistic precipitation amounts and patterns in the Alpine area. Well correlated to the prevailing westerly and north-westerly flow highest values of precipitation are mostly found in the northern upslope areas of the Alps. Switching from observation based data

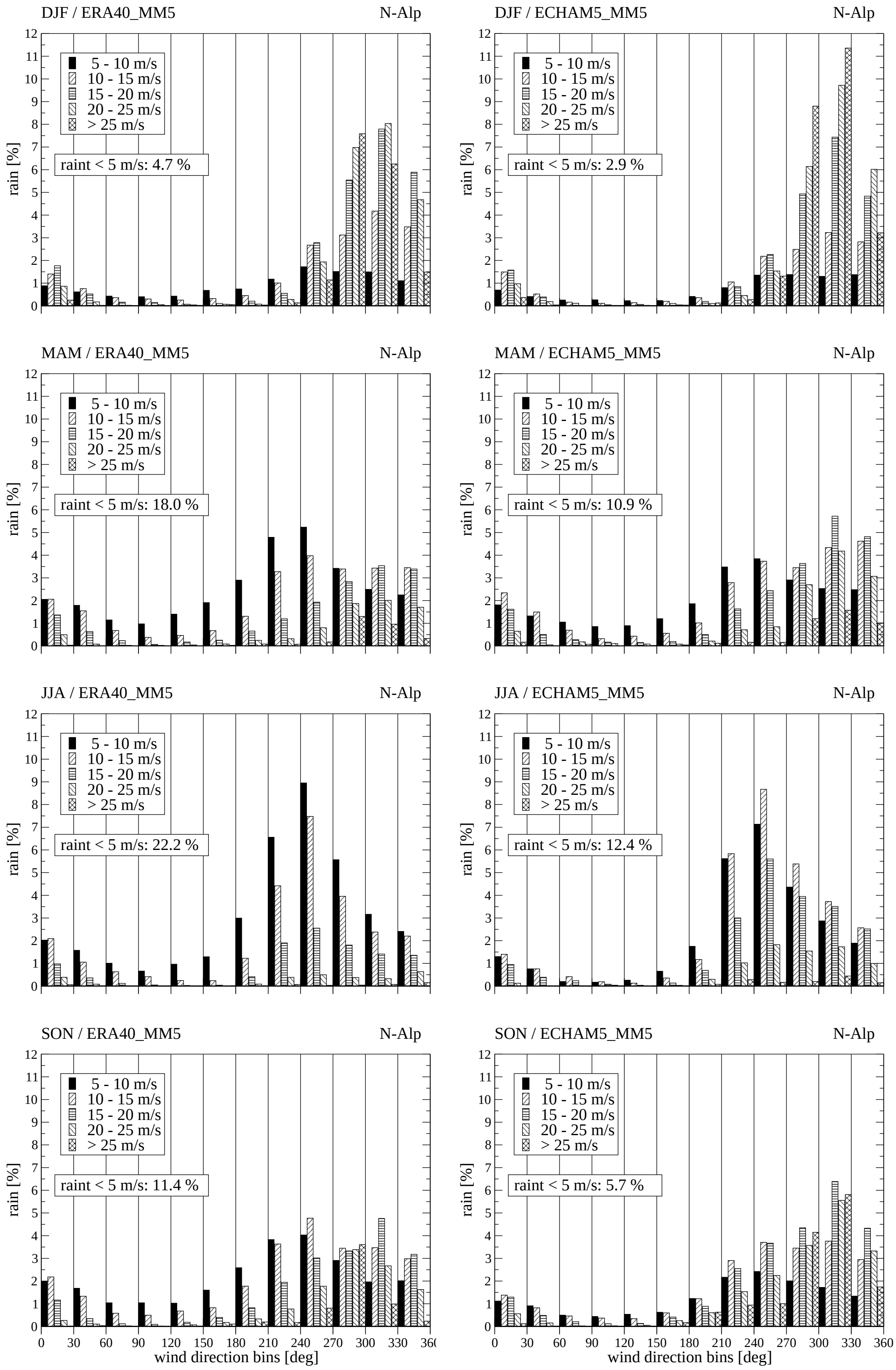


Figure 5.7: Relative precipitation amounts (1971–2000, three-hourly data) for different wind directions and wind speed classes at 700 hPa in N-Alp area simulated by MM5-ERA40 (left) and MM5-ECHAM5 (right) for each season. Relative amounts in each panel sum up to 100%

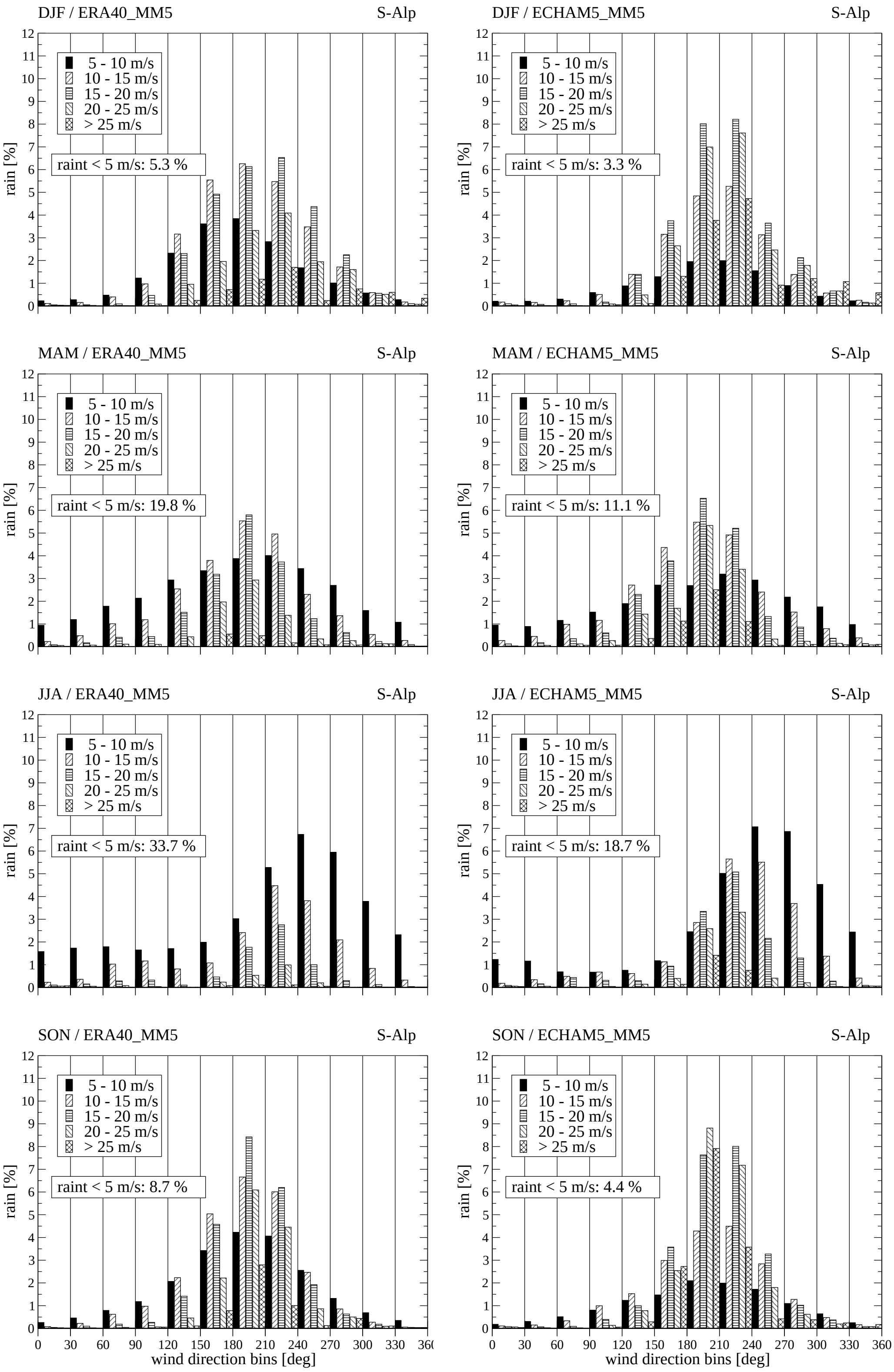


Figure 5.8: As Fig. 5.7 but for S-Alp area

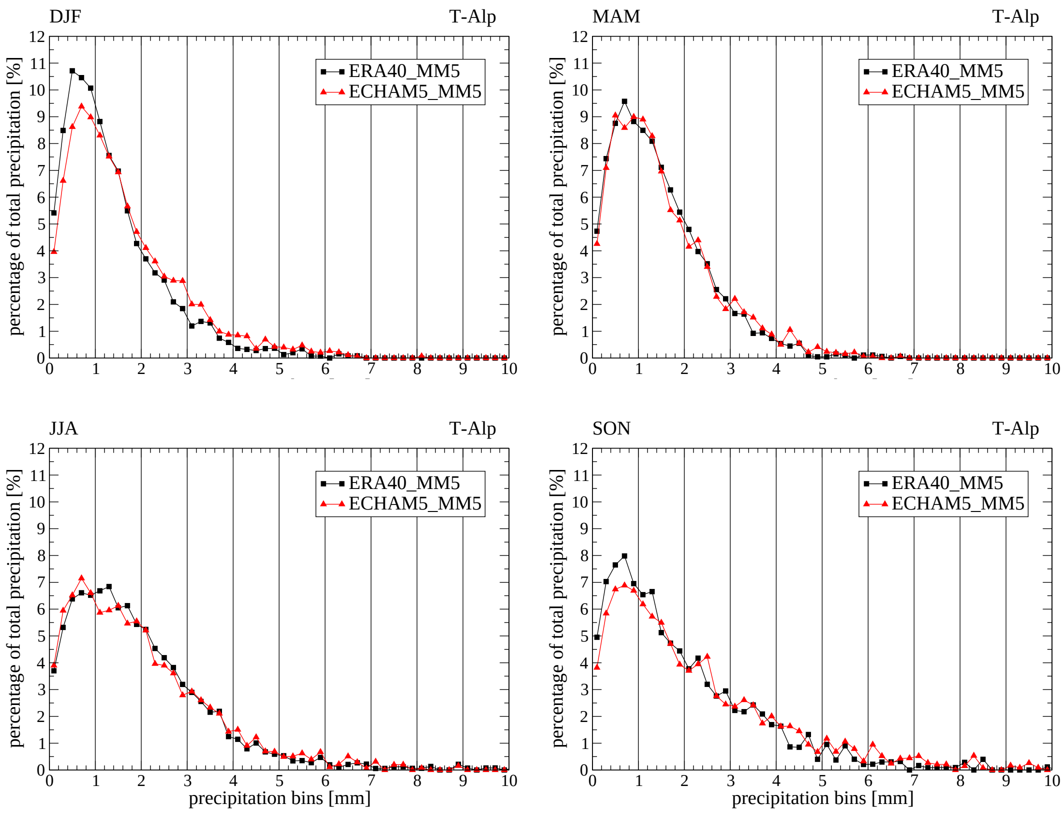


Figure 5.9: Precipitation spectra as relative contribution of 0.2 mm bins to total precipitation amount for each season as simulated by MM5 driven by ERA40 and ECHAM5 in total Alpine Area T-Alp

to corresponding global climate model simulation data (ECHAM5) for present day climate conditions brings about substantial biases in simulated precipitation. The rainfall patterns are generally intensified. In winter precipitation amounts are even almost doubled in parts of the mountainous terrain. The north and west of the remainder of the greater Alpine area also exhibits substantial surplus rainfall. A similar picture can be found for autumn. Spring shows only marginal discrepancies, whereas in summer the simulations result in a noticeable deficit of rainfall south of the Alps. Whereas ERA40 driven simulations, in correspondence with observations, exhibit only one distinct maximum in the annual cycle of mean monthly values in summer, the ECHAM5 input brings about an additional pronounced maximum in winter. The reasons for this substantial deficit in the overall simulation can be traced back to the global climate model's simulation of the large scale flow. MM5-simulated mean seasonal sea level pressure, that is strongly governed by the flow conditions given by the global input, at first sight might seem to resemble each other reasonably well for both driving datasets. Particularly in winter and autumn, however, the large low pressure system over the Atlantic ocean is slightly but discernably shifted/extended to the south. Accordingly the orientation of the mean flow relative to the Alps is changed in favour of westerly directions. A detailed analyses of the flow at the 700 hPa level (i.e. slightly above the peaks of the model orography) of three-hourly data consequently reveals more events with westerly and north-westerly wind directions as well as remarkably intensified wind speeds. Thus, the 'natural' distribution, already characterised with a maximum for westerly winds, is further accentuated, disproportionally overweighing north-westerly fractions.

The inevitable consequences on simulated precipitation are analysed separately for the most elevated areas (above 1000 m) north and south of the eastern part of the Alpine crest. Corresponding to the characteristics of the flow, in terms of its intensity and relative orientation to the Alpine crest, most rainfall due to orographic lifting in the northern part is produced in winter for north/north-westerly wind directions—comparing well to observations. The moist air from the Atlantic thus gets effectively dried, leaving not much precipitation to fall from descending air masses lee side, in the area south of the crest. This finding is generally true for ERA40 as well as ECHAM5 input. The altered flow statistics, however, lead to substantially more precipitation generated for intensified north/north-westerly wind in the northern Alpine area, resulting in the dramatic winterly overprediction. The southern part is almost not affected by more intense winds from the north. Here winterly precipitation is dominated by a comparatively broad spectrum (in terms of both, direction and speed) of southerly winds bringing moisture from the Mediterranean. ECHAM5 does not change these statistics fundamentally but entails a shift to precipitation associated with higher wind speeds, all in all also summing up to an overprediction.

The most prominent differences in terms of the analyzed precipitation vs. wind-class spectra to the situation in winter is found for summer. In the northern Alps summerly precipitation is predominantly related to low and moderate winds from the west which more or less is also true for the southern part. This behaviour corresponds well with the prevailing moderate flow, in a large scale environment with only moderate horizontal pressure gradients, roughly orientated parallel to the the Alpine crest. Switching to ECHAM5 does hardly change these spectra in terms of wind directions but again leads to an overweighed generation of precipitation due to higher wind speeds.

Beyond statistics on precipitation generation relative to flow conditions also spectra in terms of intensity of three-hourly precipitation events exhibit systematic discrepancies for the two different global input datasets. Once more, the most distinct effects are revealed in winter and to a little less extent in autumn. While the total precipitation amount still is dominated (with about 10%) by light rainfall events of about 0.4–0.6 mm/3 hours ECHAM5 input makes the regional model to noticeably reduce this fraction and to overemphasize distinctly more intense rainfall classes.

Thus, the second objective of this study has been fulfilled, i.e. the critical analysis of climatological MM5 simulations driven by ECHAM5. In summary it has to be stated, that particularly precipitation simulated by RCMs driven by ECHAM5 (or any other current GCM) are not yet suitable for a direct application in downstream impact models. The results of this section hence are somewhat less rewarding compared to the achievements presented in the previous chapter. Performing and improving global climate simulations, however, naturally is way beyond the scope of the present work. As long as the deficiencies of global models discussed above are not rectified, measures like a bias correction, as presented in the next chapter in the context of a subsequent statistical downscaling approach, have to be imposed onto the RCM's raw simulation data.[1]

[1]The findings of this chapter are also presented in Pfeiffer and Zängl 2011

Chapter 6

Statistical downscaling and bias correction / Evaluation of overall meteorological simulations in subsequent hydrology

Within GLOWA-Danube near surface meteorological fields representative for certain global climate scenarios are required at an extremely high horizontal resolution (at least from the meteorological modeller's view) of 1 km to drive the coupled, subsequent impact models. The fine-scale meteorological fields are essential for realistic simulations of the 'downstream' impact models, e.g. of the complex, non-linear hydrological processes. Case studies spanning at most several days can be simulated directly at this resolution by the means of a limited area model. Zängl et al. (2008), for example, conducted nested high-resolution simulations with MM5 for 28 hours at a horizontal mesh-size of 600 m for a small Alpine domain covering the Berchtesgaden National Park to study the small-scale precipitation variability there. Such simulations on climatological timescales, i.e. several years and decades, are, however, hardly feasible with today's computer resources. Dynamical downscaling, however, is not only preferable due to its manifold advantages compared to purely statistical approaches as discussed in the introduction, but it is essential for regional climate studies also intended, later on, to incorporate feedback effects from the underlying surface onto the regional meteorology in a direct and physically consistent way. Thus, to provide the necessary fine scale meteorological data a method had to be conceived, that on the one hand adheres to dynamical downscaling. On the other hand the computational costs for the overall downscaling process had to be reasonably limited thus still suggesting a statistical approach. The solution of this dilemma was found in a compromise implementing a combination of both approaches. As a first step dynamical downscaling is performed operating MM5 on a moderate resolution of 45 km (cf. chapter 4 and 5). Figure 6.1

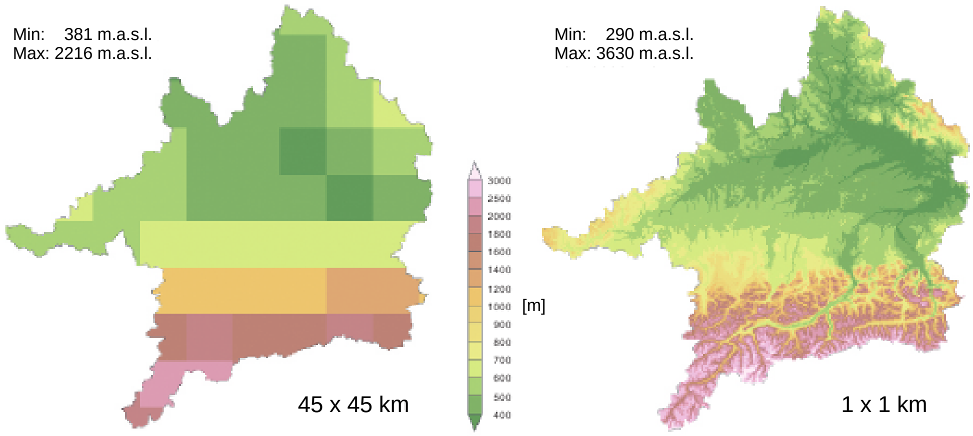


Figure 6.1: Orography of target area at horizontal resolution of 45 km and 1 km

shows the respective representation of the orography of the upper Danube catchment, as analyzed for MM5, compared to the target resolution of 1 km. A pronounced local height discrepancy between the two different datasets gets obvious—motivating quite clearly the need for further downscaling of the RCM output. Accordingly the simulation results of MM5 were further processed to the resolution of 1 km relying on a pragmatic and quite cost-effective statistical approach introduced in the following section. Additionally a bias correction has to be implemented in the downscaling algorithm that particularly accounts for discrepancies of precipitation in ECHAM5 driven MM5 simulations. The overall results of the whole meteorological modelling approach (under ERA40 as well as ECHAM5 conditions) eventually will be evaluated in the view of downstream hydrological simulations at the end of this chapter.

6.1 General concept

Figure 6.2 illustrates the very basic concept of the statistical downscaling approach. For the variable under consideration a functional relation of its value valid for each of the model's coarse grid box and each of the enclosed fine-scale grid boxes as straightforward and robust as possible has to be derived. The algorithm developed within GLOWA-Danube is based on the method of 'local rescaling' proposed by Widmann et al. (2003).

The specific method developed for the use in GLOWA-Danube basically consists of relating a high-resolution observational climatology of precipitation and a coarse scale climatology simulated by the regional model (Früh et al. 2006). Compiling a fine-scale observational climatology for mountainous areas like the Alps is by no means an easy task as has already been discussed in chapter 3.6. The unique precipitation climatology of Schwarb (Schwarb 2001, Schwarb et al. 2001) mentioned there, that was further processed according to Früh et al. (2006), serves as the observational basis

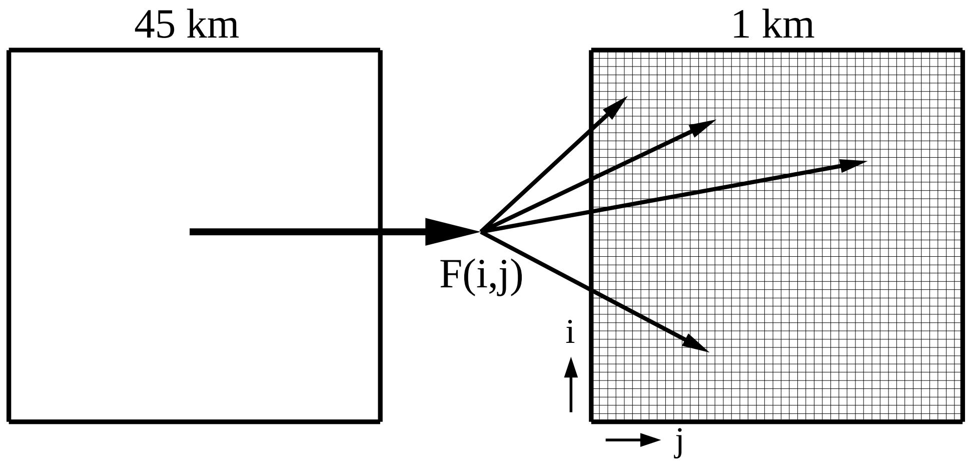


Figure 6.2: Schematic of the statistically based downscaling from 45 km to 1 km resolution

for the purpose of statistical downscaling. The corresponding present day climatology simulated with MM5 has to be driven either with ERA40 reanalysis or ECHAM5 (or any other GCM in question) data for the same period in time—depending on which global model the intended study eventually will rely on. This is essential in order to obtain consistent functional relations between observations and regional simulations. Thus, for studies on future regional climate first of all the statistical downscaling has to be prepared in a 'training period' under present day conditions, based on ECHAM5 driven MM5 simulations spanning ideally at least 30 years. This results in a set of so-called 'scaling functions' to be applied within the scaling algorithm. The MM5 simulations conducted for projections into the future (and thus naturally driven by ECHAM5 output) then have to be treated in the process of statistical downscaling with precisely these ECHAM5-MM5-specific functional relations. ERA40 driven simulations and the corresponding scaling functions, on the other hand, in principle can only serve for the necessary validation of the general concept for present day climate conditions.

The observed and simulated climatologies are evaluated on a monthly basis for the whole annual cycle. First of all the subgrid-scale variability of observations respective to the model grid boxes of the MM5 mesh in the area of interest is analyzed. To do so for each model grid box the areal average of mean monthly observations of the underlying 45 × 45 1-km grid boxes is calculated. The resulting coarse grained observational climatology is then smoothed by a bilinear interpolation onto the fine 1 km-grid giving $P^{45}_{\mathrm{obs}}(m)$ (P stands for 'precipitation', 45: (effective) resolution of 45 km, obs: observation, m: monthly value). A simple functional relation $F_{vari}(m)$ describing the fine scale variability is then obtained by building the ratio of this field and the original fine scale climatology $P^{1}_{\mathrm{obs}}(m)$:

$$F_{vari}(m) := \frac{P^1_{\text{obs}}(m)}{P^{45}_{\text{obs}}(m)}. \tag{6.1}$$

For a 'perfect' regional simulation, giving correct monthly precipitation amounts on the coarse, i.e. the 45 km grid, these monthly 2-dimensional fields could already be implemented alone, just like that, into a downscaling algorithm to calculate the desired fine-scale fields of precipitation outside the 'training period'. In practice a simple interpolation in time of the monthly 'scaling functions' $F_{vari}(m)$ to daily values $F_{vari}(d)$ might seem advisable to give smooth transitions between consecutive months avoiding any abrupt discontinuities. Extending the method to climatological evaluations on a daily basis from the start suffers from the lack of sufficient observational data on this fine temporal and spatial scale for the Alpine region. The application of the algorithm eventually consists of the multiplication

$$P^1_{sim,scal} := F_{vari}(d) \cdot P^{45}_{\text{sim}} \ , \tag{6.2}$$

where $P^1_{sim,scal}$ denotes simulated precipitation scaled down to a resolution of 1km and P^{45}_{sim} stands for the 'raw' data of the simulation on the original coarse resolution of MM5, i.e. 45 km. The granularity in time is not specified explicitly here; by construction it can be $\leq$ 1day. For the subsequent hydrological model the required hourly rain rates, simulated by MM5, were processed with the daily fields of scaling factors $F_{vari}(d)$. An explicit implementation of a diurnal cycle into the scaling functions might seem desirable, this, however, would go way too far beyond the scope of the current approach and especially the available observational data. Note here, that all operations so far are strictly mass conserving over the entire domain under consideration.

For the optimized ERA40 driven MM5 reference simulation (cf. chapter 4), showing only a marginal bias in precipitation, this downscaling approach as presented so far would be almost sufficient. Regional simulations with noticable discrepancies to observations, however, have to be subdued to an additional bias-correction to allow for realistic downstream impact studies. This is especially true for MM5 simulations nested into ECHAM5 output (cf. chapter 5). Thus, the overall downscaling algorithm also takes into account the relation of observed and simulated climatologies on the coarse grid scale of the regional model by defining a corresponding monthly factor field describing the bias:

$$F_{bias}(m) := \frac{P^{45}_{\text{obs}}(m)}{P^{45}_{\text{sim}}(m)} \ , \tag{6.3}$$

The overall scaling factor field then consists of a combination of both factor fields as

$$F(m) := F_{vari}(m) \cdot F_{bias}(m) = \frac{P^1_{\text{obs}}(m)}{P^{45}_{\text{sim}}(m)} \ , \tag{6.4}$$

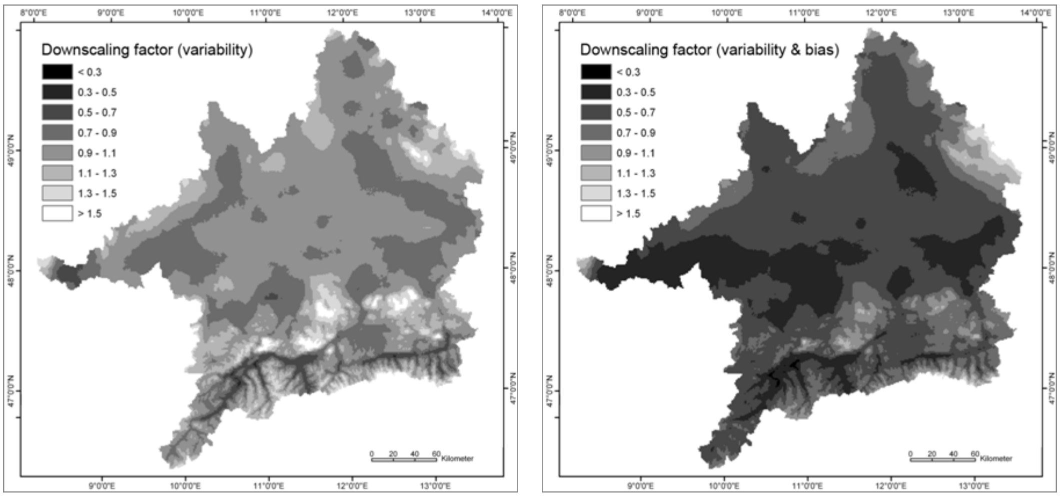


Figure 6.3: Field of scaling factors for precipitation in January; correction for subgrid-scale variability only $F_{vari}(m)$ (left) and additionally with bias correction $F_{vari}(m) \cdot F_{bias}(m)$ (right)

resulting effectively in a relation of observed fine scale and simulated coarse climatology, that has to be multiplied with the simulated fields of precipitation after an interpolation to daily values $F(d)$:

$$P^{1}_{sim,scal} := F(d) \cdot P^{45}_{\mathrm{sim}} \ , \qquad (6.5)$$

Figure 6.3 exemplarily shows on the left scaling functions $F_{vari}(m)$ for January, where the influence of the fine scale orographic structure on precipitation in the Alpine area is clearly recognizable. The factor field on the right additionally considers the bias correction (i.e. $F_{vari}(m) \cdot F_{bias}(m)$) necessary particularly under ECHAM5 conditions, reflecting the predominant overprediction of precipitation in the greater Alpine area that has to be corrected for before the use in subsequent impact models.

Compared to additive methods a multiplicative correction offers the advantage, that it does not lead to negative precipitation rates in cases of negative anomalies by construction. It also preserves or rather accentuates the temporal dynamics of simulated rainfall events. Simulated dry conditions, on the other hand, in any case stay dry under the downscaling process, which in many situations will be the most probable and realistic option. Früh et al. (2006) evaluated this approach, in an early stage, applied to precipitation simulated by MM5 for a set of meteorological situations demonstrating a substantial benefit of this quite cost-effective method. Further encouraging results of verification against ground-based observations and compared to data provided by satellite retrieval are presented in Früh et al. (2007).

In principle, also other meteorological variables can be treated by this downscaling procedure. It has been, however, further refined within the present study, in the course of the last project phase of GLOWA-Danube. Thus, for near surface temperature a similar approach has been chosen as for precipitation with a 'split-up' between subscale variability and grid scale bias. For temperature, however, an additive correction approach was applied, such as to replace all divisions and multiplications with corresponding calculations of differences and summations in the equations above. This is appropriate to the nature of the fairly systematic relation between temperature and orography height and last but not least as there is no need to avoid resulting negative values as in the case of precipitation. Surface pressure altitude correction to the fine scale grid in the final version of the downscaling tool is performed according to the barometric formula using the local mean value of coarse scale and fine scale (already downscaled) temperature fields (cf. Cosgrove et al. 2003).

6.2 Sensitivity to flow regimes

A possible shortcoming of every statistical downscaling approach is its somewhat unclear validity and robustness under altered climate conditions in the future. Do the statistical relations between large scale predictors and high resolution predictands, derived under present day conditions, hold under climate change? To address this issue the downscaling approach presented above got extended in a pragmatic way to also take into account the ambient flow conditions in the downscaling procedure. This is accomplished by setting up the downscaling functions separately for different flow regimes analyzed concerning the wind direction in the higher Alpine region at 700 hPa, well above the underlying model orography. Especially in elevated mountainous terrain altered statistics of flow regimes might entail noticeable impacts on precipitation patterns and amounts. Wind data are evaluated and grouped according to wind directions, revealing their relative frequency of occurrence (cf. fig. 5.6). Events with wind speeds below a threshold of 5 m/s are assorted to a 'weak wind' class. The wind direction classes are then redimensioned in a way to allow for an even distribution of all events to each single class. Thus the predominant and most frequent westerly winds are sorted into two separate bins with directions from 240° to 270° and 270° to 300°, whereas comparatively infrequent easterly winds are collected in a class with a rather wide span from 30° to 150°. All in all 6 groups were defined as shown in table 6.1.

For each of these wind direction classes separate functional relations are derived from the respective associated observed and simulated climatological precipitation patterns on a monthly or seasonal basis. Possibly altered relative occurrences of the specific large scale flow regimes under a changing future climate are then automatically accounted for and properly weighted within the algorithm by applying the individual corresponding specific downscaling functions.

Tests of this extended approach are analyzed and summarized by Schipper et al. (2010), all in all showing only marginal improvements compared to the basic method, at least in the area of interest investigated. In the further course of the project GLOWA-

Wind direction		
group 1	240° - 270°	(WSW)
group 2	270° - 300°	(WNW)
group 3	300° - 030°	(N)
group 4	030° - 150°	(E)
group 5	150° - 240°	(S)
group 6	weak wind	< 5 m/s

Table 6.1: Wind direction groups as defined for the wind dependent downscaling approach

Danube it is fallen back accordingly on the wind-independent method—not the least to save valuable and scarce computing resources. The study by Schipper et al. (2010), however, was nonetheless quite important so as to prove the robustness of the original approach applied to the upper Danube catchment.

6.3 Application and evaluation in hydrology

The final section of this chapter is dedicated to the presentation of some specific validation results using the example of a hydrological (climate impact) model driven with the MM5 simulations conducted for this thesis, nested in ERA40 or ECHAM5, and further processed by the statistical downscaling approach as explained in the first section. The hydrological model used is the physically based, uncalibrated hydrological process model PROMET (Processes of Radiation, Mass and Energy Transfer) described by Mauser and Bach (2009). In the current setup it covers the upper Danube catchment at a resolution of 1 km resulting in 77.000 raster-elements and is generally operated on a time step of one hour (Marke et al. 2010). PROMET amongst other things accounts for the influence of a dynamically interacting vegetation and of snow/ice on the land-atmosphere mass and energy fluxes. Validation of the simulations is performed against measurements at the discharge gauge of the watershed at Achleiten near Passau. Meteorological input data accordingly have to be provided hourly at the resolution of 1 km. The required meteorological parameters are precipitation, near surface temperature, wind speed, air humidity, incoming short- and longwave radiation, and surface pressure. The simulated discharge thus constitutes an integrated response to the meteorological forcing. Statistical downscaling of wind speed and air humidity follows the same procedure as for precipitation. Due to the lack of fine scale observations of incoming radiation variables on climatological timescales they are merely bilinearly interpolated onto the 1 km grid.

Figure 6.4 shows mean monthly discharge ('MMQ') at gauge Achleiten for a continuous simulation over the years of 1972 to 2000 under ERA40 and ECHAM5 conditions compared to observations. Depicted are results for different complexities of the statistical downscaling, i.e. for plain bilinear interpolation ('bil'), for downscaling only correcting for subgrid-scale variability ('vari') according to the $F_{vari}(d)$ scaling functions, and finally for the full approach ('vari&bias') with combined scaling functions $F_{vari}(d) \cdot F_{bias}(d)$, i.e. with additional bias-correction. With ERA40 as the driving global dataset the simulations with uncorrected, only bilinearly interpolated MM5 input reflect the annual cycle of the discharge already reasonably realistically. They feature, however, some overestimation of MMQ in the first half of the annual cycle and in December that gets particularly noticeable in May. This can barely be rectified by incorporating the fine scale variability into the downscaling process. Slightly better (here: lower) results in spring are contrasted by little poorer (here: too high) values for June. Activating the bias-correction allows for significantly more realistic overall discharge values with no general annual overprediction. Only the timing of the peak discharge is somewhat shifted from June/July to May. In the colder seasons the agreement between observation and simulation is almost perfect. The reason of the somewhat too early maximum in discharge probably lies in the non-linear character of hydrological processes. The hydrology in the Upper Danube catchment in spring and early summer is strongly influenced by snowmelt. Any seemingly minor inaccuracies in the simulation of each single variable during this time of the year might entail significant consequences due to the complex interplay of meteorology and the underlying surface covered with snow and ice. In the view of these considerations it gets obvious that it is not clear a priori to what exact relative extent a correction of precipitation, temperature or each of the other meteorological variables contributes to the improvement in simulated discharge in certain situations. Furthermore, even at the rather high resolution of 1 km an additional subgrid-scale approach especially for the treatment of snow and ice might be necessary to improve the simulations. In complex orography like the higher Alpine regions a considerably high variability in the distribution of snow and ice can be found even within a 1 km $\times$ 1 km grid box. Last but not least in an area like that a three dimensional calculation of radiation could significantly improve the simulations—simulations thus at quite substantially higher costs, though, that are not (yet?) feasible on climatological timescales.

Switching global climate to ECHAM5 conditions the hydrological simulations with RCM data, that are not corrected for any bias, lead to an annual cycle of mean monthly discharge that is characterized by substantial overprediction in the colder seasons and in spring, with a peak again in May. This corresponds well with the massive overprediction of precipitation primarily in winter that is due to the discrepancies in the simulated large scale flow of the driving global boundary data as analyzed in chapter 5. The surplus discharge in May, however, that is comparable to the results under ERA40 conditions, obviously is not caused by a precipitation bias but is rather due to too warm (uncorrected) temperatures in snow and ice covered higher Alpine regions. The overall bias correction induces a significant improvement of the discharge simulation

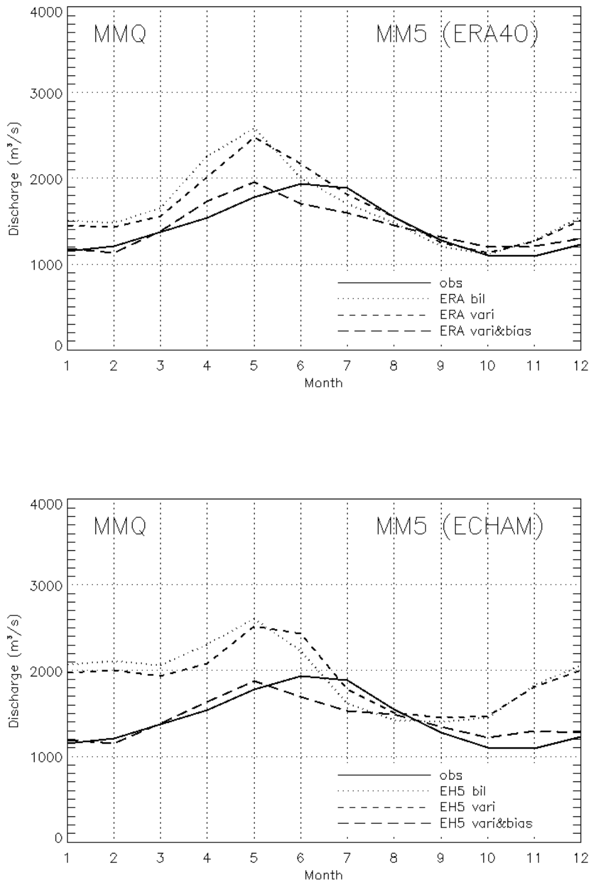


Figure 6.4: Mean monthly discharge at gauge Achleiten observed and simulated by PROMET with ERA40-MM5 (upper panel) and ECHAM5-MM5 (lower panel) forcing and for different complexities of statistical downscaling; bilinear interpolation (bil), impressed subgrid-scale variability (vari), additional bias-correction (vari&bias)

that is eventually well on a par with the simulations under bias corrected ERA40 conditions.

Figure 6.5 offers a different perspective on the hydrological simulation. Here the number of days reaching a certain threshold of simulated discharge are depicted. Again plain bilinear interpolation as well as downscaling without bias correction of the meteorological input is not sufficient to remove the discrepancies to observations. Only additional bias correction allows for practically optimal simulations. Any mere temporal shifts, as identified in the annual cycle above (cf. Fig. 6.4), naturally cannot be seen in this kind of diagramm. The slight discrepancies in the timing of mean monthly discharge amounts indeed obviously get effectively compensated over the whole year as can be roughly deducted from Fig. 6.4. Otherwise the almost perfect match of simu-

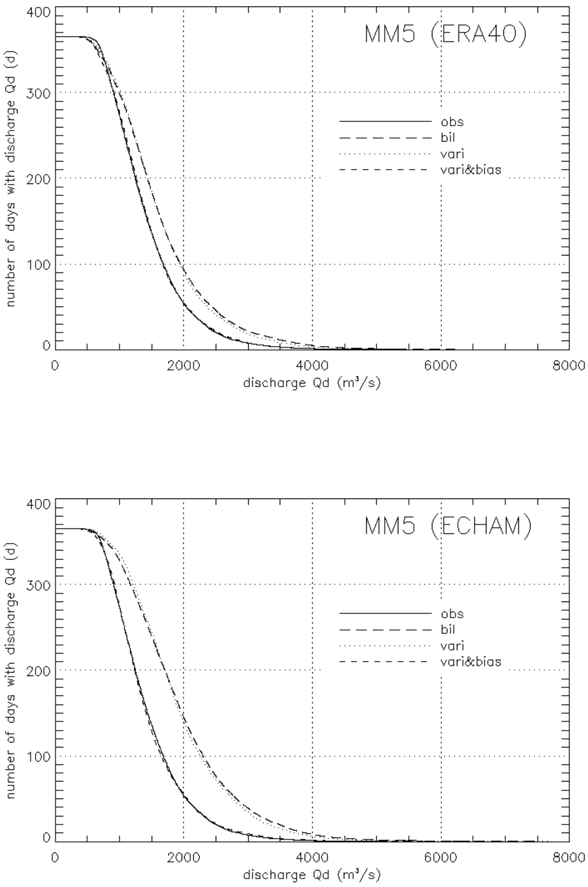


Figure 6.5: Spectra of daily discharge at gauge Achleiten, cf. figure 6.4

lated and observed daily discharge spectra would not be possible. The situation under ECHAM5 conditions presents itself similar to that under ERA40 showing, however, substantially overestimated discharge values for 'raw' meteorological input corresponding to the monthly means.

6.4 Summary and Discussion

The impact models of GLOWA-Danube depend on meteorological input data at an extremely high horizontal resolution of 1 km. This cannot be accomplished on climatological timescales by regional climate modelling alone. However, for several reasons outlined in the introduction of this dissertation, it was decided on the implementation of a RCM within the overall GLOWA-Danube modelling system. Particularly, it is one of the aims of GLOWA-Danube, and thus of the present work, to establish an interactive link later on between regional climate simulations and the regional and local landsurface/vegetation, dynamically modelled by one of the climate impact models (i.e. PROMET) that is also to be integrated in the overall model composite. This cannot be fulfilled in principle by a statistical downscaling approach and inevitably requires a regional climate model. Hence, a new two-stage method is applied such as to process GCM output with a regional model onto an 'intermediate' resolution of 45 km in a first step. The second downscaling step resorts to a statistical, climatology based downscaling algorithm as presented in the current chapter. In this way GLOWA-Danube benefits from the advantages and options of both, dynamical and statistical downscaling, and this, last but not least, with reasonably limited overall requirements of computational resources.

The statistical downscaling approach implemented for GLOWA-Danube builds upon the work on 'local rescaling' of Widmann et al. (2003). Their method proved to be nearly equally effective as more sophisticated (and expensive) approaches while at the same time being quite easy to implement. They used GCM-generated precipitation as predictor for the downscaling of precipitation. This approach, however, in many cases will suffer from the poor quality of the simulated large scale rain. In GLOWA-Danube, though, precipitation provided by a regional model serves as predictor, that is already quite realistic for the specific region of interest, particularly when driven by observational global data—a circumstance that is clearly beneficial to obtain high-quality statistically downscaled, high-resolution precipitation data even in the upper Danube catchment with its very complex orography. The specific method as devised for GLOWA-Danube thus essentially bases on the comparison of a high resolution climatology for the area of interest (at the target resolution of 1 km) and a corresponding GCM-RCM simulation climatology, valid in a training period of 30 years. In short, mean monthly fields of observations are basically divided by corresponding simulation data, resulting in high resolution fields of correction factors valid for each variable and each month. The desired daily resolution is accomplished by a simple interpolation in time of monthly fields. The availability of climatological observations is limited to monthly data, hence a priori it is not possible to perform the comparison to simulation data on a daily basis. The actual downscaling algorithm is designed in a 'slim and slender' fashion such as to impress the fine scale variability as well as a correction for coarse scale biases onto the required meteorological field in one single calculation step. This is done by simply multiplying the corresponding high resolution field of correction factors, derived in the training period, with the actual coarse grained field to be downscaled, issued by the RCM for the required point in time.

Tests of an extended approach, additionally also considering various regimes of the large scale flow, did not bring about noticeably altered results. This finding essentially proved the validity of the original 'straightforward' approach for the region of interest also under changing climate conditions. It also implies that climatological relations between large scale fields and fine scale features for the variables considered are quite robust in the area of the upper Danube catchment. This, however, might not hold true for other regions of the world.

All in all, from the perspective of the hydrological impact model the validation of regional present day climate simulations conducted with MM5 (with the configuration identified and optimized within this study) and further processed by statistical downscaling proves to be quite encouraging and promising also for studies under climate change. Mean monthly discharge values of the upper Danube catchment simulated by a hydrological model that was driven with corresponding high resolution meteorological input data for 1972–2000 were analyzed against observations at the gauge at Achleiten near Passau. Under ERA40 data as input to the meteorological model chain (RCM + statistical downscaling) they showed already a reasonable annual cycle without any bias correction applied. ECHAM5 input on the other hand entails overall substantial overprediction apart from the months July to September. This had to be expected from the remarkable surplus precipitation amounts in the colder seasons simulated by MM5 under an ECHAM5 environment as revealed in chapter 5. Engaging bias correction in both cases leads to an almost perfect hydrological simulation of the total annual discharge, only with a shift of the observed discharge peak from June/July to May in the simulation. Furthermore, also simulated daily discharge values agree very well with observations as soon as the bias correction is applied to the meteorological variables. The shift of the discharge peak even with bias corrected precipitation is related to the highly complex and non-linear hydrology, particularly in mountainous terrain. Here the discharge is a result of an entangled interplay of various meteorological as well as soil and surface variables (Strasser 2008). Particularly in spring, when the situation is more or less favourable for snowmelt and thawing soils, already minor discrepancies in any of the simulated meteorological variables can have substantial effects on the simulated hydrology. Kunstmann and Stadler (2005) also report deficiencies in runoff simulated by the hydrological model WaSiM (latest description by Schulla and Jasper 2007), driven by high-resolution MM5 simulations (2 km), in the comparatively small Mangfall catchment over a one-year period under conditions of snow-melt as well as snow-accumulation. Furthermore, in complex terrain such as the Alps a resolution of 1 km in some aspects still might be to coarse. Within a 1 km × 1 km grid box, for example, a considerable variability of snowy and icy patches interspersed with rocks and patches overgrown with grass and shrubs can be found in nature, some of which shadowed by fine scale topographic features others lying in bright sunlight—thus, all in all features not captured in detail by the models involved. In the view of this high degree of complexity the results achieved in discharge modelling can already be considered as excellent. Naturally, however, there is still room for improvements. Bernhardt et al. (2010), for example, performed a study on snow transport at a 30 m grid for the highly complex terrain of the Berchtesgaden National Park. They used a catalogue of wind fields simulated with MM5 at a resolution of 200 m, that were further downscaled to 30 m, and achieved good correspondence of simulated values of snow water equivalent compared to observations.

The good correspondence of simulated river discharge driven by bias-corrected MM5 data and observed values, reached so far, is by no means self-evident. This statement is corroborated by an intercomparison study with meteorological fields simulated by another regional model called REMO (with even higher horizontal resolution of 10 km, Jacob 1997) and processed with the identical downscaling algorithms (Marke et al. 2011). Even though monthly simulated and downscaled precipitation amounts are identical to observations by construction for each regional model, the temporal variability on shorter timescales (down to the hour) of rainfall intensities can affect the highly non-linear hydrological simulations substantially. This consideration also holds true for other meteorological variables, like e.g. near surface temperature, treated with a similar downscaling technique as precipitation.

The overall approach on downscaling of GCM output investigated in this study and evaluated in the present chapter in the context of subsequent hydrology fits well in current pertinent research efforts. Leung et al. (2003), for example, recommend coordinated 'end-to-end' systems to test the respective downscaling approaches directly in the view of impact research rather than 'patching together' isolated studies on modeling and impacts, each of which aimed at disparate goals. Fowler et al. (2007) call for more studies on downscaling that concentrate particularly on impact in subsequent hydrology. These requirements are well met by the present study, as it was designed from the very beginning in close cooperation with the hydrology group of GLOWA-Danube, such that the meteorological output was tailored adequately to the specific needs of the hydrological model. Furthermore, Leung et al. (2003) see the driving GCM input as first order source of uncertainty. This concern is specifically addressed within the present study by the intercomparison (down to the hydrological impact) of data generated by ERA40 and ECHAM5 serving as input to the overall model chain. As a result the basic need for bias correction, especially under a global GCM-generated meteorology, was corroborated here. Bias correction was as well seen as indispensable for successful GCM-RCM driven impact studies by Fowler et al. (2007) in their review on statistical and dynamical downscaling techniques in the view of applications in downstream hydrology. Whereas Fowler et al. (2007) investigate the respective pros and cons of statistical and dynamical downscaling the present study successfully combines both approaches to benefit from the respective advantages of both methods as outlined in the introduction.

Salathe et al. (2007) focus on statistical downscaling and the impacts of climate change on hydrology in the Pacific Northwest of the United States. They perform, however, also a RCM simulation finding mesoscale responses that are not captured by (pure) statistical approaches. Particularly the loss of snow and increased cloudiness, simulated by the RCM, altered the radiation budget in their research area leading to locally enhanced warming. Dynamical downscaling in their view is preferable but unfortunately too demanding with respect to computational resources. Thus, the work of this study again presents itself as a valuable compromise by resorting to a combination of a RCM (at a moderate horizontal resolution) and further statistical downscaling.

Themessl et al. (2010) recently investigated several statistical downscaling and bias correction approaches in the Alpine area. For actual climate applications they suggest methods that can be calibrated with corresponding RCM simulations driven by GCM control runs to correct for the combined GCM-RCM error (irrespective of where the actual error is generated)—a prerequisite fulfilled ideally by the approach presented in the present chapter. Additionally, the present study allowed for a clear identification of deficiencies that can be tracked down to the driving GCM data (cf. chapter 5).

Concluding this chapter it can be stated that also the third goal of this thesis could be accomplished successfully: The overall meteorological modelling approach, as devised within the present study, including the statistical, bias-correcting downscaling algorithm allows for highly realistic simulations of the downstream hydrology in the upper Danube catchment.[1]

[1] The concepts and findings of this chapter are also presented in Früh et al. 2006, Schipper et al. 2010, Marke et al. 2010, 2011

Chapter 7

IPCC's A1B scenario—results on the regional scale in the upper Danube Catchment

In the course of this thesis so far a specific configuration of MM5, used as a regional climate model, has been identified, optimized and evaluated under observation based as well as GCM generated input for applications in the upper Danube catchment. Furthermore the design and application of an additional, bias-correcting statistical downscaling technique has been refined and evaluated particularly in the view of subsequent hydrology. Thus, a sound basis is laid to address the primary (meteorological) task of GLOWA-Danube, i.e. to project the regional characteristics of future global climate change valid for the upper Danube catchment and its complex fine scale orography.

The present chapter thus is intended as short excursus to illustrate exemplarily the application of the overall downscaling approach for a specific global change scenario and to present the corresponding results valid for the upper Danube catchment, that had to be provided to the other groups of GLOWA-Danube.

Within GLOWA-Danube all participating groups agreed upon the intermediate A1B scenario as proposed by IPCC (Nakićenović and Swart 2000, IPCC 2001, cf. fig. 2.4 and fig. 2.5) that results in an average global warming of around 3.7 K at the end of the 21st century according, for example, to ECHAM5 simulations. The somewhat more extreme A2 scenario (4.2 K) was rejected by the GLOWA-Danube scientists to evade any possible criticism of undue 'alarmism' that might be brought forward by the stakeholders of the project. The A1B scenario in any case is already quite dramatic in terms of expected global temperature rise. The B1 scenario on the other hand, with its additional 2.5 K around the year 2100, meanwhile is judged by the scientific community as no longer within reach and hence as too optimistic. Thus it is no longer of much interest for climate impact studies depending on a global basis that is reasonably close to (a possible) reality.

The respective A1B global scenario simulation (i.e. member number one of three equivalent simulation runs, each of which with a slightly different initialization) for the 21st century conducted with ECHAM5 (thus consistent with the setup of the validation) is processed within this study by the combined dynamical-statistical downscaling approach illustrated in the chapters above. The regional, fine scale results of this modelling chain, as analyzed and discussed in the present chapter, are provided to the other disciplines of GLOWA-Danube and their subsequent impact models. Thus, goal number four of this thesis is addressed.

Assessing climate change and its possible impacts careful evaluation of simulated signals is crucial. In the beginning of the project discussions on simulation results and the corresponding climate change signals to be expected sometimes lead to some mutual confusion and misunderstandings between the different working groups. It then became clear that each stakeholder of the project has a very specific question and thus a corresponding relevant planning horizon or timescale. This requires a very specific view of each stakeholder onto climate change signals. This is illustrated exemplarily in the following on the one hand by first of all analyzing long-time linear trends. Comparing mean values of two certain subperiods on the other hand might lead to somewhat different conclusions.

7.1 Linear trends of climate change signal

Figure 7.1 first of all depicts the temporal evolution of the annual mean climate change signal of 2-m temperature and precipitation in the 21st century as simulated by ECHAM5. The base period comprises the years 1971 to 2000. The evaluation and averaging of ECHAM5 data is performed on 5×5 ECHAM5 grid boxes (horizontal resolution about 300 km) amply covering the upper Danube catchment. The results of the global model are only presented for reference. ECHAM5 is not expected to give particular dependable and meaningful data on the regional scale, especially in a region with rather complex orography such as the Alpine area. In order to assess regional change further downscaling of the global model's simulations to high resolution patterns of key variables is indispensable.

Figure 7.2 shows in an analogous manner the temporal evolution of MM5-simulated data (nested in ECHAM5, with further downscaling to 1 km, including the bias-correction), spatially averaged exactly over the upper Danube catchment on the 1km grid. For comparison also corresponding results for the regional model REMO (Jacob 1997, 2008) are shown.

A distinct rise of annual temperatures beyond the reference period gets obvious for all model simulations. From the year 2035 on the annual mean temperature of every single year is higher compared to the reference value. For precipitation additionally a ten year running mean is depicted for a more convenient visualization of the general trends against the background of a quite high interannual variability. After no clear

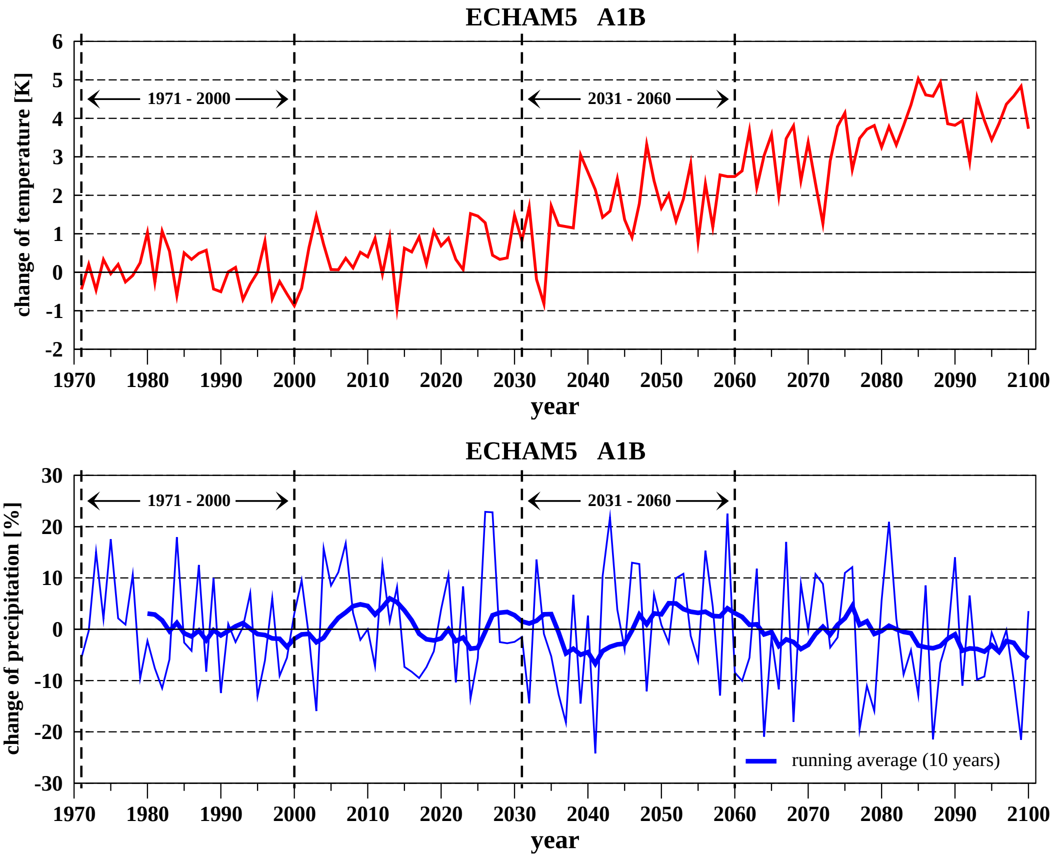


Figure 7.1: Climate change signal for the 21st century compared to mean of the years 1971-2000 in the upper Danube catchment. Annual mean of near surface temperature (upper panel) and annual precipitation (lower panel). Simulated according to an A1B scenario by ECHAM5.

long time trend in the first half of the 21st century a decrease of annual precipitation amounts beyond the year 2050 has to be noted.

All corresponding curves are quite similar, as expected since both regional models are driven by the same ECHAM5 simulation. Some more differences occur for annual precipitation as simulated by the regional models, that are probably due to its rather complex generation. At the beginning and the end of the 21st century also some discrepancies in temperature stand out with MM5 being up to 1 K cooler than REMO. Particularly at the end of the 21st century this is correlated to somewhat more rain simulated by MM5. Thus the lower near surface temperature here might be caused e.g. by an altered bowen ratio for wetter soils or more cloudy situations influencing the radiation balance at the surface during the respective periods.

In table 7.1 the long time linear trends for the years of 1990 to 2100 are broken down to single seasons for ECHAM5, $MM5_{vari\&bias}$, and $REMO_{vari\&bias}$. Note that due to the additive nature of downscaling and bias correction of temperature the respective curves

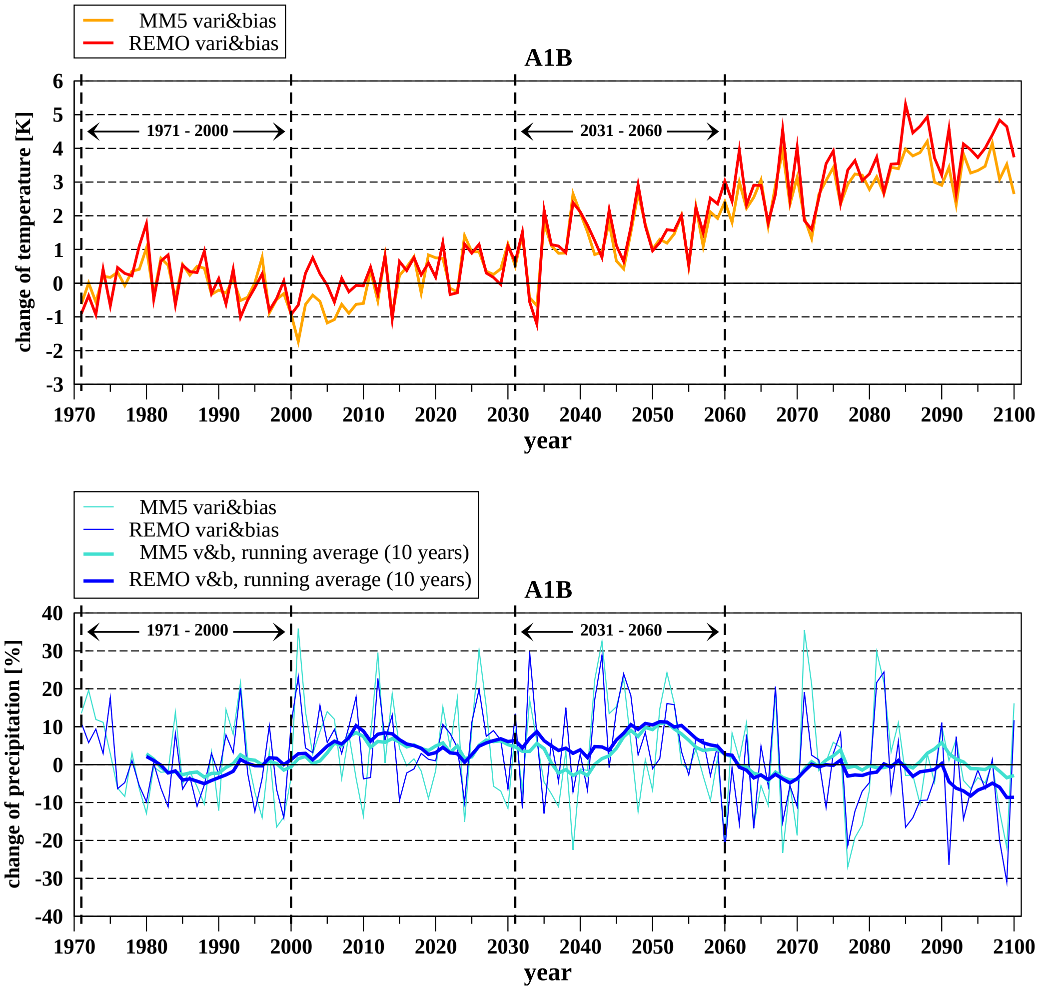


Figure 7.2: Climate change signal for the 21st century compared to mean of the years 1971-2000 in the upper Danube catchment. Annual mean of near surface temperature (upper panel) and annual precipitation (lower panel). Simulated according to an A1B scenario by ECHAM5, dynamically downscaled with MM5, further statistical downscaling and bias correction

	ECHAM5	$MM5_{vari\&bias}$	$REMO_{vari\&bias}$
DJF	+6.4	+5.2	+6.7
MAM	+3.3	+3.2	+3.7
JJA	+5.5	+5.8	+5.3
SON	+5.0	+4.8	+5.1

Table 7.1: Linear trend (years 1990 to 2100 relative to mean of 1971-2000) of temperature change [K] in the Upper Danube Catchment according to figure 7.2

	ECHAM5	MM5	$MM5_{vari\&bias}$	REMO	$REMO_{vari\&bias}$
DJF	+12.8	+7.7	+8.4	-4.9	-1.4
MAM	+3.5	+13.1	+14.5	+9.1	+10.7
JJA	-34.1	-28.7	-29.4	-31.4	-32.6
SON	-1.1	-1.0	-2.7	-14.5	-12.6

Table 7.2: Same as table 7.1 but for precipitation [%]

and values for difference signals for $MM5_{vari\&bias}$ and 'raw' MM5 data are identical. This naturally is not true in the case of precipitation (see table 7.2) with downscaling functions based on multiplication. The linear trends in temperature show highest values in winter for REMO and ECHAM5 with up to 6.7 K exceeding MM5 by 1.5 K. MM5 on the other hand predicts the most intense rise of temperature in summer with 5.8 K, whereas REMO gives the lowest, yet still remarkable increase with 5.3 K. The overall discrepancies might seem to be marginal. It has to be kept in mind, though, that e.g. in winter even slightly higher (mean!) temperatures might entail substantial changes in the hydrological regimes. Thus, for example, even only comparatively short periods with warm(!) rain instead of snow falling onto snow and ice can lead to massive flooding. Linear trends of changes in precipitation are to be taken from table 7.2. Here for comparison also 'raw' MM5 data are included reflecting the non-linearity of the corresponding downscaling process. All simulations agree upon a dramatic decrease of precipitation in summer with values of up to -34 %. In spring, in contrast to the global model with only a marginal increase, the regional models feature quite noticeable more rain with up to +14.5 %. For autumn generally a decreasing tendency is to be expected, with substantial values, however, only according to REMO. The situation for winter is more or less undecided with a noticeable increase in ECHAM5 of 12.8 % and a little less increase according to MM5 but contradicted by REMO with a deficit of up to -4.9 %.

Note that for climate change impact research also changes of spatial patterns of key variables (cf. next section and GLOWA Danube's Global Change Atlas, Mauser et al. 2010) play an important role.

7.2 Climate change signals from different timeslices

A common method in climate change studies consists in building difference signals between two temporally averaged (regional) climate model runs, each comprising 'timeslices' of e.g. about 30 years, for the future and for present day conditions (Machenauer et al. 1998, Hagemann et al. 2009, Schwierz et al. 2010). This procedure was originally not the least motivated by the hope to eliminate systematic model deficiencies, that should occur in an identical manner for both simulation periods, and thus to get a robust, realistic climate change signal. This method, however, might at worst also obstruct the view on the actual shortcomings of the model in question. The need to neutralize systematic model errors by such means naturally should be overcome by improving and properly adapting the models as far as possible—the great progress in this field made over the last decades is quite encouraging. Furthermore, for certain technical purposes, such as to drive dynamical impact models or to perform transient climate change studies, explicit individual timeseries of climate simulations are indispensable. For the meantime bias corrections like the one presented and discussed in this study (cf. chapter 6) serve as a valuable working solution to tackle existing simulation discrepancies. Accordingly, not only the difference signal for two different periods but the actual downscaled, bias-corrected values of both annual cycles of mean monthly values are presented here for temperature and precipitation. This additional different view on climate change might also prevent non-experts from misunderstanding a curve like in figure 7.2, that strictly only can be seen as a single member of a whole large statistical manifold of possible future developments under the assumed global trend, and not in a way as to actually expect a certain value in reality as rendered for a specific year.

Figure 7.3 depicts the annual cycle of mean monthly 2m temperature as simulated by $MM5_{vari\&bias}$ and $REMO_{vari\&bias}$ driven with ECHAM5 data for the years of 2031 to 2060 compared to the period of 1971 to 2000. The particular future time period goes back to requests of GLOWA-Danube's stakeholders and their typical planning intervals for investments e.g. in the field of hydraulic engineering. Due to the construction of the downscaling algorithm both curves for the present day climate are identical independently of the RCM used. For both models the climate change signal in the annual cycle is quite similar. Apart from April, with practically no change, discernible higher temperatures occur all over the year with highest values in August for MM5 and in January for REMO, each around 2 K. This conforms to the findings above, analyzing the linear trends with a general minimum of temperature rise in spring and a distinct maximum for REMO in winter and a somewhat less clear maximum for MM5 in summer. The extent of the climate change signal in this period is already substantial yet still comparatively moderate in the view of the change to be expected at the end of the century.

The corresponding annual cycle of mean monthly precipitation is shown in figure 7.4. Summing up the monthly values results in an increase of annual precipitation for

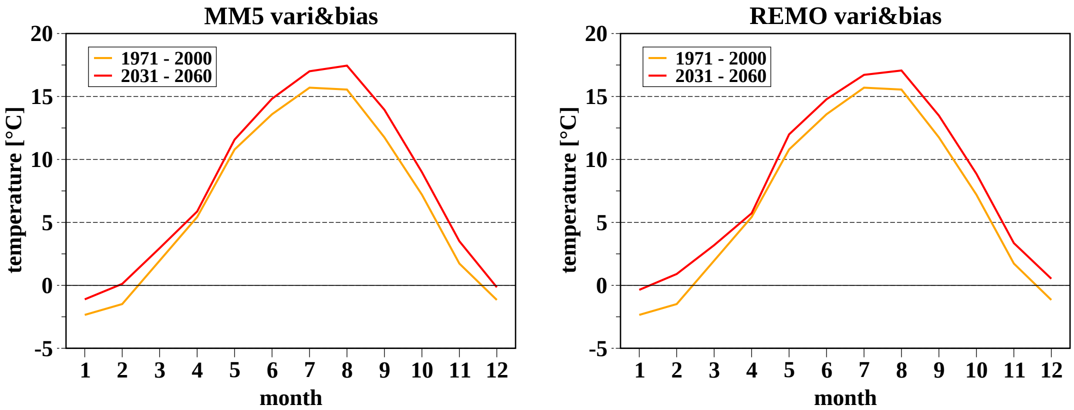


Figure 7.3: Annual cycle of mean monthly 2m temperature [°C] in the upper Danube catchment for the years of 1971 to 2000 and 2031 to 2060 as simulated under ECHAM5 conditions by MM5 and REMO and further downscaled including bias correction

	$MM5_{vari\&bias}$	$REMO_{vari\&bias}$
DJF	-3	+2
MAM	+27	+32
JJA	-6	-13
SON	+19	+38

Table 7.3: Seasonal changes of precipitation amounts [mm] in the Upper Danube Catchment according to figure 7.4

both RCMs in contrast to the negative linear trend for the years of 1990 to 2100. This also gets obvious in the corresponding timeseries depicted in the lower panel of figure 7.2. Here, several years in the period 2031–2060 are characterized by considerably more precipitation compared to the reference, i.e. the mean of 1971–2000. The few comparatively drier years cannot compensate for that. Generally, in this period, REMO tends to produce more annual precipitation than MM5. Table 7.3 shows the seasonal changes between both periods. Particularly in autumn noticeable positive values turn into a more or less moderate decrease in the long-term trend, a change most distinct for REMO.

Figure 7.5 presents the spatial patterns of present day and future conditions of near surface temperature for the two periods considered as simulated by $MM5_{vari\&bias}$. The corresponding fields for $REMO_{vari\&bias}$ (not shown, see GLOWA-Danube's Global Change Atlas, Mauser et al. 2010) are quite similar. For temperature naturally a close correlation to terrain height gets obvious. In figure 7.6 the difference signal between future and present day fields is depicted for both models. The effective resolution here is reduced to the original horizontal resolution of the respective RCM, i.e. 45 km for MM5 and 10 km for REMO. This is due to the additive nature of the downscaling

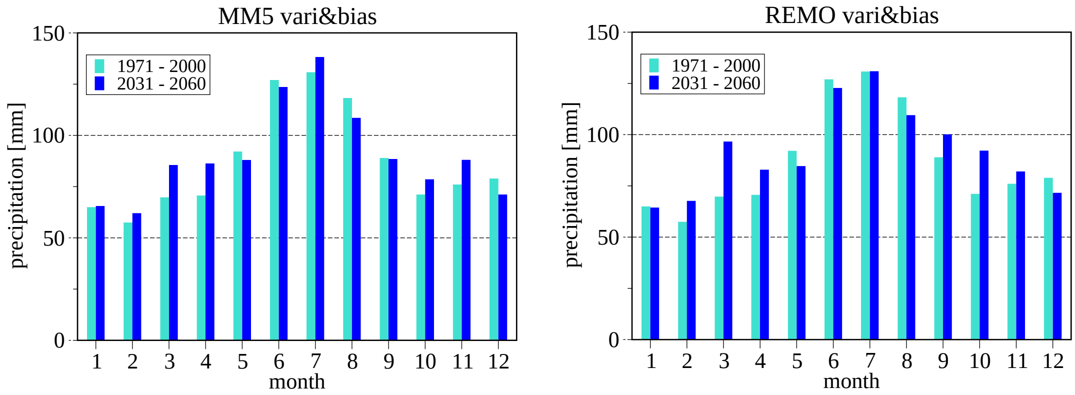


Figure 7.4: Annual cycle of mean monthly precipitation [mm] in the upper Danube catchment for the years of 1971 to 2000 and 2031 to 2060 as simulated under ECHAM5 conditions by MM5 and REMO and further downscaled including bias correction

algorithm for temperature. For both RCMs the change of temperature features a distinct gradient with higher values in more elevated areas in the south reaching up to 1.6 K (MM5) and 2.3 K (REMO). To the north these values go down to about 1.2 K, with REMO generally reaching somewhat higher values over the entire analysis domain. The higher values in elevated and particularly Alpine terrain is probably connected to altered surface energy budgets in the future that, amongst others, react most sensitive to altered durations and extensions of snow and ice cover.

In figure 7.7 the spatial distribution of precipitation simulated with $MM5_{vari\&bias}$ is depicted for both periods. The results for REMO present themselves mostly similar in an analogous diagram (not shown, cf. GLOWA-Danube's Global Change Atlas, 2010). A distinct gradient with higher values in the south and in some correspondence to terrain height gets obvious. Highest precipitation amounts, however, are found in the Alpine foreland, whereas most elevated areas are substantially drier. The respective climate change signal is given in figure 7.8. For precipitation, that is processed with multiplicative downscaling functions, finer details on the 1 km grid are still discernable. Whereas $REMO_{vari\&bias}$ generally predicts more future precipitation compared to $MM5_{vari\&bias}$ the overall pattern of the changes agree to a large extent. More precipitation is simulated particularly in the north-eastern part of the Alpine foreland and a little less pronounced in the area of the Bavarian Forest in the north-eastern part of the upper Danube catchment. A substantial decrease of precipitation is to be noted in the most south-westerly part of the analysis domain.

All in all $MM5_{vari\&bias}$ and $REMO_{vari\&bias}$ seem to produce quite similar, yet clearly not identical results. $REMO_{vari\&bias}$, however, revealed some deficiencies in the context of subsequent hydrological modelling of discharge in the upper Danube catchment already under present day conditions (Marke et al. 2011). $MM5_{vari\&bias}$, on the other hand, performed excellent with the the same hydrological model PROMET (cf.

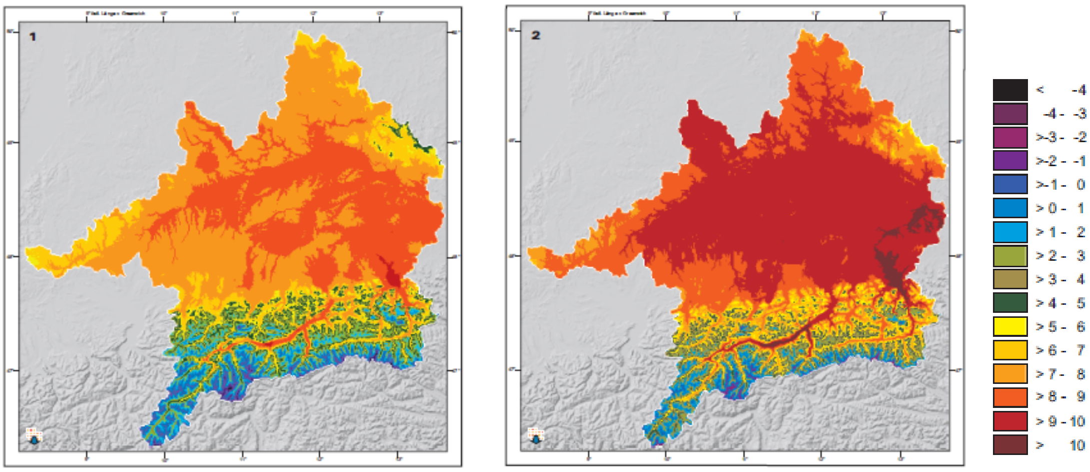


Figure 7.5: Mean 2m temperature [°C] for the years of 1971 to 2000 (left) and 2031 to 2060 (right) as simulated under ECHAM5 conditions by MM5 and further downscaled including bias correction

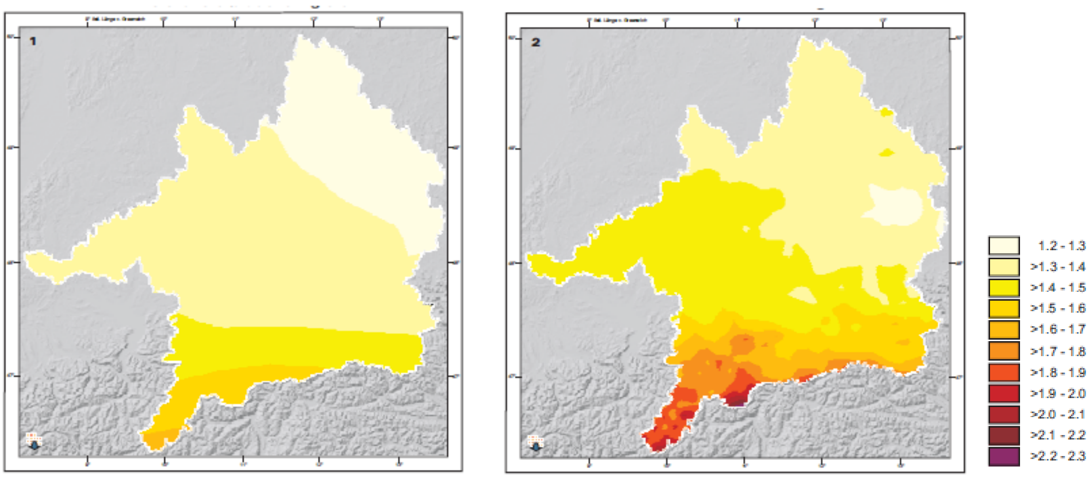


Figure 7.6: Difference of mean 2m temperature [K] for the periods of 2031 to 2060 against 1971 to 2000 as simulated under ECHAM5 conditions by $\text{MM5}_{\text{vari\&bias}}$ (left) and $\text{REMO}_{\text{vari\&bias}}$ (right)

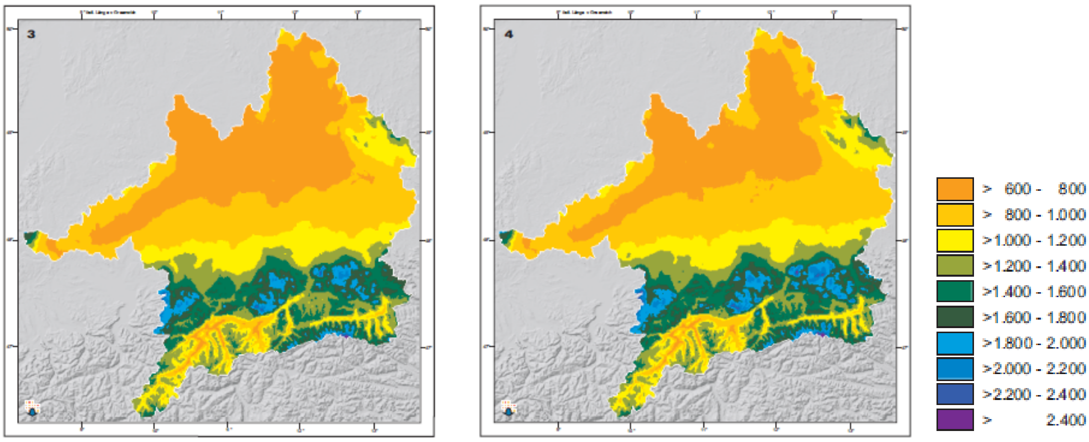


Figure 7.7: Mean annual accumlated precipitation [mm] for the years of 1971 to 2000 (left) and 2031 to 2060 (right) as simulated under ECHAM5 conditions by MM5 and further downscaled including bias correction

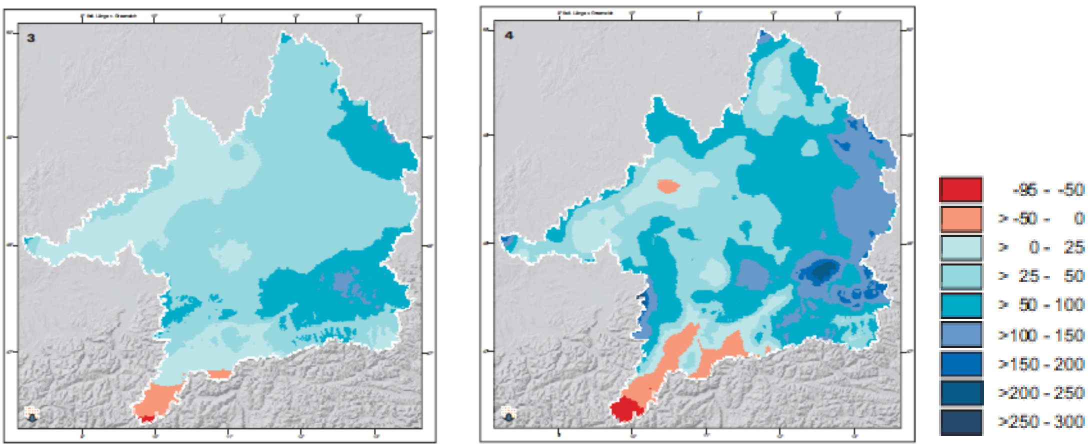


Figure 7.8: Difference of mean annual accumlated precipitation [mm] for periods of 2031 to 2060 against 1971 to 2000 as simulated under ECHAM5 conditions by $MM5_{vari\&bias}$ (left) and $REMO_{vari\&bias}$ (right)

previous chapter). As present day climatological mean monthly values of simulated, downscaled and bias-corrected meteorological data are identical (by construction of the downscaling algorithm) to observations this suggests some problems of REMO in capturing properly the dynamics of atmospheric processes in the complex Alpine terrain (cf. GLOWA's Global Change Atlas, chapter S5, 2010). Thus, amongst other factors, a higher horizontal resolution of a regional model does not necessarily lead to an improved simulation.

7.3 Summary and Discussion

A substantial climate change in the upper Danube catchment, particularly in the second half of the 21st century, is to be expected according to the long-time simulation performed for this thesis. The comparatively late onset of this change on the one hand might be advantageous for the societies affected such as to have still some more time left to devise appropriate measures of adaptation. On the other hand, due to the gentle transformation of the prevalent climate regime in the first decades of the century, the relevant decision makers mistakenly might come to the conclusion that the change eventually will not be substantial at all and no actions are necessary to be taken.

The various methods of the analysis, and first and foremost the timeslices and timescales considered, might lead to quite different conclusions, particularly for simulated precipitation changes. Thus, the results of climate change scenarios have to be conveyed quite comprehensively as well as carefully tailored according to the context and the timescales relevant for the pertinent decisions and adaptations in question.

Mean annual temperature and precipitation, simulated with $MM5_{vari\&bias}$ as well as with $REMO_{vari\&bias}$, are quite similar at first sight, as they are strongly governed, as any other nested regional model, by the driving input data. The complex processes, however, lead to noticeable differences primarily for the first decade and for about the last 15 years of the 21st century. Non-linearity, differences in physics parameterizations and intricate feedback effects obviously cause a somewhat different development of regional climate conditions. Already marginal differences can lead to substantially different impacts, not the least in view of the highly complex and non-linear hydrology, as was shortly addressed in the previous chapter. This is particularly true in snow or ice covered areas with complex orography (mountains!) where the ambient temperature is close to the freezing point and small discrepancies in the simulations might entail a 'switch' of the current regime.

Clearly, an overall temperature rise under a global A1B scenario for both regional climate simulations can be stated. The linear trend (110 years) results in an increase of up to 5–7 K for winter and a still considerable surplus of around 3.5 K in spring. The patterns of the difference signal between 2031–2060 and 1971–2000 as well reveal a general increase of temperatures. Here a distinct, roughly north-south gradient, more or less following the orography with highest values in the mountainous areas, is simulated with both models. The more pronounced increase of temperatures in the Alps is probably due to reduced fractions of areas covered by snow and ice in the future. Thus, whereas a major part of the surface's energy budget under present day conditions serves to melt snow and ice, it will be converted more and more to sensible heat in the future.

For precipitation the picture is considerably more complicated. The timeseries indicates a discernible decrease of annual precipitation amounts in the second half of the current century. This gets reflected in the linear trend over the whole century and is due to substantial rain deficits, first of all in summer, of roughly -30 % according to both, $MM5_{vari\&bias}$ and $REMO_{vari\&bias}$. These deficits can not be balanced by additional precipitation, that is to be expected in spring accounting for about +10 to +15 %, following the two regional models. Winter and autumn are somewhat undecided, with comparativley small changes, but as well do not turn around the decreasing tendency of annual precipitation sums. Consulting the mean monthly differences for the two 30–year time periods of 2031–2060 and 1971–2000, however, results in an noticeable increase of future annual precipitation amounts. This is on the one hand due to a substantial surplus in spring of around +30 mm that in its tendency seems to be robust as well in the long-time linear trend. Even more strikingly, the negative values in autumn, found in the linear trend, are turned into noticeable positive contributions. Thus, particularly $REMO_{vari\&bias}$ jumps from moderate but non-negligible negative values to almost +40 mm. The extreme deficits in summer, as analyzed in the linear trend, are somewhat less distinct in the mean 30–year timeslice differences (around -10 mm), whereas winter here shows only marginal changes. The patterns of simulated precipitation are quite similar for both 30–year periods and are both governed by orographical features, generally reflecting rain generation by orographic lifting. The difference signal roughly reveals a west–east gradient, particularly for $REMO_{vari\&bias}$, with relatively more surplus precipitation in the eastern part of the upper Danube catchment. A pronounced deficit, however, is simulated in small areas of the south-western tail of the analysis domain.

It has to be kept in mind, though, that the data gathered by the simulations presented here only represent two technical realisations of a whole manifold of possible future (regional) climate scenarios. The actual range of climate change will naturally remain somewhat uncertain—due to a variety of uncertanties, such as, e.g., concerning various aspects of future (global) socioeconomic development and also due to remaining technical deficiencies of the models employed. Thus, in order to prepare for climate change in the region of interest and to develop proper adaptation strategies extensive studies have to be performed based on whole sets of such simulations with the whole model chain from GCM to RCM to statistical downscaling. These sets on the one hand should comprise various realisations of the the same global scenario by properly disturbing the corresponding simulations (global and regional) to give an idea of the 'inner-scenario' variabilities. On the other hand various members of the overarching global scenario families (i.e. A1B, A1, B1, B2, etc., cf. IPCC 2007) should be considered in parallel. This, naturally, involves huge costs with respect to computational and, not the least, also human resources, that go beyond the possibilities of the project GLOWA-Danube.

Naturally, some work in this sense already has been done or initiated. Under the umbrella of the European project PRUDENCE (Christensen et al. 2007a), for example, various groups pooled and analyzed their results of regional climate simulations based on up to four driving GCMs and ten RCMs, with horizontal resolutions mainly of about 50 km. However, not all possible combinations of the available GCM and RCM were considered (i.e. simulated with the RCM) and primarily only one IPCC scenario, the A2 scenario, was taken into account. Christensen and Christensen (2007) evaluate the results for various European subregions in terms of 2m temperature and precipitation, trying to at least roughly identify the relative importance on the results of the driving GCM vs. the RCM employed. Furthermore they provide guidelines for the selection of certain appropriate subsets of all their available regional simulation data for the use in specific climate change studies. Hagemann et al. (2009) performed GCM-RCM (ECHAM5-REMO) simulations for the 21st century for the B1, A1B and A2 scenarios at a resolution of 50 km, focussing on the large European catchments of the Baltic Sea, the Rhine and the whole Danube. The results of the upper Danube catchment, presented here, and the overall Danube catchment are unfortunately not directly comparable. ENSEMBLES (2009) is another quite more extensive multimodel (GCMs and RCMs) project, in the framework of which regional climate simulations at 25 km horizontal resolution were performed under A1B scenario conditions for Europe and West Africa. Here, missing members in the GCM-RCM simulation matrix were filled by a pattern scaling approach (Kendon 2010) or based on the analysis of variance (Déqué 2011) to save computational resources. These techniques, however, cannot fully substitute an actual RCM simulation but rather only can give a more or less reasonable estimate.

The present chapter illustrates the applicability of an obviously well designed and properly validated new downscaling approach. It establishes a robust and direct link from global climate modelling to fine-scale regional climate scenarios at an extremely high resolution of 1 km, required by subsequent impact models. The approach presented can readily be applied to other IPCC scenarios simulated with a GCM and thus may well contribute to more extensive future studies investigating climate change and its possible spread with the help of comprehensive ensembles. The results based on the A1B scenario are provided as requested for the use in the subsequent climate impact studies and models of the overall project (see, e.g., also GLOWA-Danube's Global Change Atlas 2010)—thus one more task of this thesis is met successfully.[1]

[1]The analyses and findings of this chapter are also presented in Marke et al. 2009

Chapter 8

Interactive coupling of MM5 to the landsurface-vegetation-hydrology model PROMET

One of GLOWA-Danube's primary aims is the creation of a combined overall model named DANUBIA to simulate all relevant aspects (from the view of socioeconomic as well as natural sciences) of the water cycle in the Upper Danube catchment. The primary principle established in this context is a clear separation of responsibilities of each single discipline and the corresponding model component according to the respective particular core competences. Any 'doubling' of identical variables, i.e. variables simulated by two different sub-models in parallel at the same time, bringing about ambiguous results or 'loose ends' should be avoided. This principle at first was not (and could not—due to early model deficiencies, see following sections) adhered to concerning the interplay of regional meteorological simulations by MM5 and the landsurface-vegetation-hydrology model PROMET. In fact, some variables governing or representing exchange processes at the interface between atmosphere and underlying landsurface, like the surface heat fluxes, were simulated by MM5's NOAH-LSM as well as by PROMET. Thus it was agreed to implement a strict separation and an unambiguous coupling mechanism within the overall system after a thorough individual validation of each of the two model components. A worthwhile benefit in view of the meteorological simulation was expected from the more advanced and detailed algorithms and the extremely high internal horizontal resolution of PROMET. This should allow to simulate landsurface and vegetation processes more realistically compared to the landsurface module provided by the MM5 system. Eventually, this should also effectively lead to a better simulation of the atmosphere, that is inevitably influenced by its lower boundary. PROMET was successfully operated for the simulation of the hydrology in various river catchments (Mauser and Bach 2009) and thus obviously is well capable of reproducing e.g. inner-soil (vertical and horizontal) water transport as well as evapotranspiration by the vegetation (according to stomatal resistance, photosynthesis, etc.) and soils. Furthermore it has available highly reliable, high-resolution soil, landuse, and vegetation data for the Upper Danube Catchment and meanwhile also for the Central European region. MM5 on the other hand allows for highly realistic regional simulations of the most relevant key variables in regional climate impact studies, i.e. precipitation and near surface temperature, as has been demonstrated in the previous chapters of the present study. Nevertheless, exchanging the interactively operated landsurface module of MM5 with PROMET cannot be expected to perform satisfactorily without comprehensive mutual adjustments of both model components (Chen and Dudhia 2001). Thus, the final aim of this thesis, the results of which are presented in this chapter, by no means is easy to achieve.

8.1 Setup of coupling

The meteorological variables (valid at the lower most level of MM5) necessary to drive the landsurface model PROMET (Mauser and Bach 2009) are: temperature, precipitation, air humidity, pressure, wind speed, incoming diffuse and direct solar radiation, and longwave radiation. All fields are processed by the downscaling algorithm discussed in the pertaining chapter above. The landsurface/vegetation scheme in return gives back to the atmosphere: sensible and latent heat flux, momentum flux, and upward short and longwave radiation. Additionally to these energy fluxes also the ground temperature has to be supplied by PROMET. This, together with the temperature in the lowest atmospheric level, enables the routine simulating the exchange processes in the planetary boundary layer to determine the effective stability regime.

The 450 km $\times$ 450 km domain covering the upper Danube catchment, where generally all simulations and evaluations take place, naturally is, beyond the basic technical feasability, way too small for meaningful simulations in a two-way coupled mode. In any even only moderate advective situations the air getting in touch with e.g. fluxes of latent and sensible heat from the underlying surface or vegetation would have left the domain already before it could give back any significant responses as an interactive feedback within the coupling area. Thus, for the interactively coupled mode between MM5 and the underlying surface the domain where coupling takes place had to be widened substantially to an area of around 1200 km $\times$ 1200 km, covering central Europe and focussing on the upper Danube catchment (cf. fig. 8.3).

Due to technical restrictions in the use of PROMET concerning availability of necessary high-resolution (1 km) landsurface data as well as sufficient computing resources it was not possible to extend the simulations of PROMET und thus the interactive coupling to the overall simulation domain of MM5. Outside the area where PROMET simulates the landsurface conditions the original landsurface scheme of MM5, the so-called NOAH-LSM, has to fill in. To allow for systematic intercomparison studies with respect to both landsurface models the NOAH-LSM can be run 'online', i.e. in parallel to PROMET, also within the coupling area in the technical setup conceived for this study. The fluxes calculated by the NOAH-LSM within the PROMET area, however, are not fed in to MM5 but are saved to an external file for offline analysis versus the corresponding PROMET data. This measure proves quite valuable in the process of adapting the models to be coupled.

Within the MM5 package the NOAH-LSM, that is essentially required for the outer parts of the simulation domain, only works with two different schemes of the planetary boundary layer. One of these schemes is the Mellor-Yamada style, so-called Eta-PBL, that was chosen for the reference simulation successfully validated in chapter 4. This scheme, however, proves to be more or less 'hardwired' to the surface, not least as a clear separation of the implicitly interwoven ground temperature and the surface's heat fluxes obviously is not possible with reasonable effort. These fields on the other hand have to be processed and issued to MM5 in a 'one-by-one' fashion by PROMET. Thus the Eta-PBL practically is incompatible with PROMET. The other PBL-scheme working with the NOAH-LSM is the MRF- or Hong-Pan-PBL (Hong and Pan 1996), that allows for an unambiguous data transfer of every single variable to be exchanged between atmosphere and surface. Thus, for the two-way simulations presented in this chapter the Eta-PBL is replaced in favour of the MRF-PBL. Preparatory test simulations relying on the MRF-scheme also produced quite promising results, thus corroborating the decision to switch schemes in context of the interactive coupling.

8.2 Preparatory tests

To identify the most critical sensitivities some basic preparatory test simulations were conceived for this study and are shortly discussed in the following. First of all the time step of the coupling had to be reduced considerably from one hour (the standard within DANUBIA) to nine minutes to properly capture the dynamical responses of the coupled system and thus to avoid any systematic drift in the simulations. In the one way coupled mode, that relies without difficulty on an hourly input of meteorological data to PROMET, any possible drift of the overall system will be suppressed, at least in the long term mean, by the inalterably and indepedently prescribed meteorological fields. The lower time step, however, is more consistent with the typical time scales of relevant atmospheric processes, valid, e.g., in the development of deep convection. In the setup of the present study this new coupling frequency equals exactly four intrinsic time steps of the MM5 (135 seconds). The impact of the coupling frequency is illustrated in figure 8.1 where the temporal evolution of various variables of MM5 at the lowest model level are depicted for a short sensitivity test comprising a simulation time of 240 hours at the beginning of June 1995. Here, MM5 simulations with an artificially lengthened coupling time step to its own landsurface module of 10 and 60 minutes is evaluated against a control run with the original MM5 intrinsic time step of 135 seconds. The sensitivity tests are actually not conducted in an absolutely free-running manner. Rather the variables simulated by the landsurface module in the control run are stored in an external file. The respective 'snapshots' of these pre-recorded fields, each valid at the matching point in time of the simulation (i.e. every 10 or 60 minutes, respectively), are then coupled back to the atmospheric part in the sensitivity runs. Doing so the overall system should be prevented from drifting all too excessively. However, even in this special setup to test the sensitivity of the coupling only after a rather short simulation time the longer time step of 60 minutes clearly can lead to substantial discrepancies, that may or may not get aligned back in an actual truly free running long-time simulation. Considerable differences occur e.g. for temperature in the second half of the simulated period. This corresponds to altered downward solar and longwave radiation as well as vertical velocity indicating non-negligible differences in cloud formation. Thus, eventually also precipitation rates are noticeable influenced by the choice of the coupling time step. This behaviour of this specifically constricted one-way coupled system further motivates a substantially reduced coupling time step, even against the background of generally limited predictability The shorter time step of 10 minutes on the other hand seems to be 'safe', allowing for a moderate, tolerably biased simulation and thus is a valid compromise in the view of additionally required computing resources. Note here, that the respective 'coupling time step' will also be the effective intrinsic numerical time step of PROMET.

Further prepatory test simulations focus on the sensitivity of MM5 to the simulated surface heat fluxes supplied to the atmosphere. Particularly the relative partitioning of sensible and latent heat flux is of some interest as an early version of PROMET only calculated evapotranspiration (i.e. latent heat flux) explicitly, whereas sensible heat flux resulted as a residual from the surface energy budget. Thus, in a small set of test runs the bowen-ratio is artificially disturbed by setting the latent heat flux to $\pm$ 20 % of the values gathered and stored to file from a control run. The sensible heat flux correspondingly is enhanced or reduced such as to conserve the original sum of both heat fluxes. These altered surface fluxes are then fed into the atmosphere in the same manner as described above for tests of the time step, which is in this case set to 60 minutes. Thus, something like a 'worst cast scenario' of the simulations is set up, with a somewhat inappropriate long coupling time step combined with presumably too large inaccuracies of the simulated Bowen-ratio. The corresponding results are presented in figure 8.2. Low level atmosphere temperature and moisture react very soon as these model variables are most directly influenced by the altered surface fluxes. A lower latent heat flux and thus a higher sensible heat flux more or less inevitably favours higher near surface temperatures as long as no more complex processes start up. In the further course of the simulation also the variables of downward short- and longwave radiation show some noticeable reaction suggesting differences in the buildup of clouds. Furthermore the boundary layer dynamics also seem to be affected

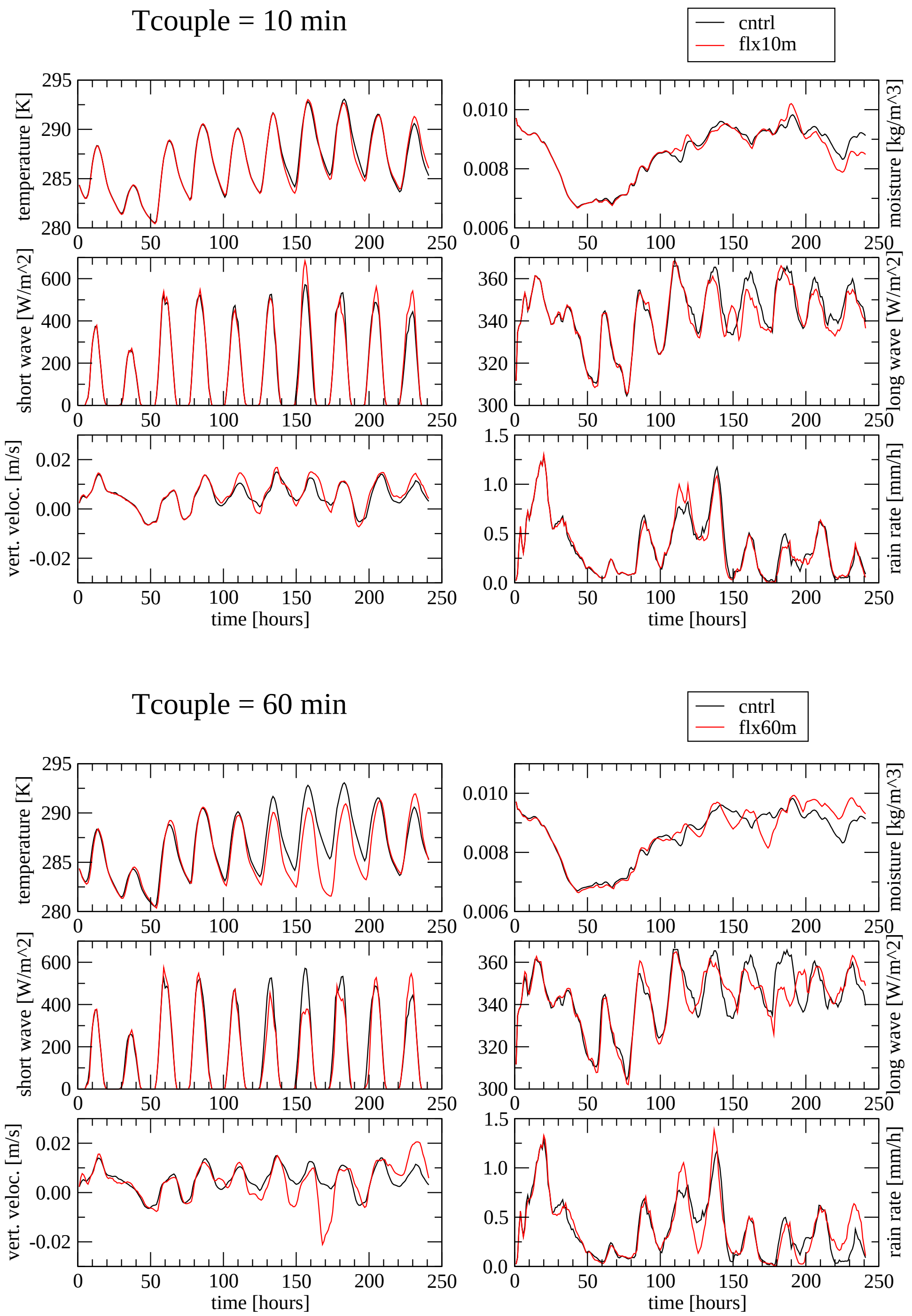


Figure 8.1: Near surface data as simulated for 240 hours starting 1st of June 1995 with MM5 coupled to its own landsurface module. Control run 'cntrl': landsurface is called and coupled at every MM5 intrinsic timestep of 135 seconds. Sensitivity tests 'flx10m', 'flx60m': fluxes from surface module as calculated and stored in 'cntrl'-run coupled into MM5 every 10 (upper panel) and 60 minutes respectively (lower panel)

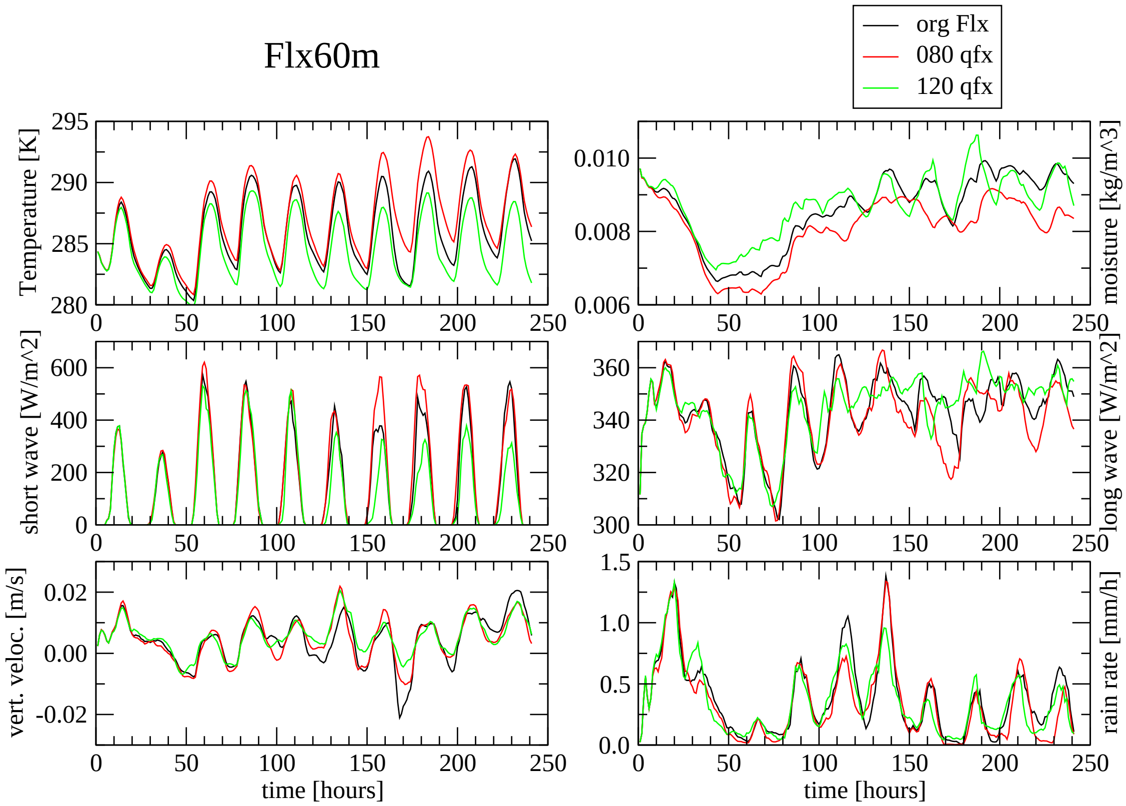


Figure 8.2: Near surface data as simulated for 240 hours starting 1^{st} of June 1995 with MM5 coupled to its own landsurface module. Control run 'cntrl': landsurface is called and coupled with unaltered surface heat fluxes for every MM5 intrinsic timestep of 135 seconds. Sensitivity tests: '080qfx'/'120qfx' with latent heat flux reduced/enhanced 20%, sensible heat flux readjusted to keep total sum of heatflux constant. Surface fluxes are coupled every 60 minutes into atmosphere

regarding the behaviour of near surface vertical velocity. The mechanisms between altered latent heat flux (and thus moisture) entering the atmosphere and the generation of clouds and rain are, naturally, quite complex and might be, to some extent, 'counter-intuitive'. They do not necessarily follow a straightforward soilmoisture-precipitation recycling feedback (cf. Schär et al. 1999, Hohenegger et al. 2009). Thus simulated rain rates as in figure 8.2, for example, may well be highest for lowered surface moisture fluxes. Especially in the boundary layer the interplay between variables and conditions such as surfaces fluxes, advection, turbulence, stability etc. can sometimes lead to somewhat unexpected results. Higher sensible heat fluxes, e.g., might lead to a higher and drier planetary boundary layer unfavourable for the generation of clouds and rain. On the other hand higher sensible heat fluxes may also spur upward motions of air masses eventually triggering convection if sufficiently moist and unstable air is advected (Findell and Eltahir 2003).

8.3 Interactive coupling with PROMET

After these investigations of key sensitivities of the interactive coupling approach MM5's landsurface module is replaced within the inner part of the original simulation domain with the highly sophisticated landsurface-hydrology model PROMET. Figure 8.3 juxtaposes the respective landuse classifications underlying both landsurface models. First of all the distinctly higher resolution of 1 km versus 45 km gets obvious featuring an enormous additional amount of information (Zabel 2010). Furthermore, substantial differences in both datasets have to be noted. The comparatively coarse MM5 grid does not capture any sealed urban areas that show up at the high resolution of PROMET. Thus, e.g. in the center of the GLOWA-Danube research area the urban agglomeration of Munich gets 'visible'. Additionally the greater lakes and high Alpine glaciers get discernible. Even more influence on the regional meteorology and its simulation should be expected from the substantial fraction of rocky areas in the Alpine mountains represented in the high resolution data set. According to the dataset underlying the landsurface module of MM5 on the other hand, central Europe at a 45 km resolution is only a composite of undifferentiated agricultural and forestal areas. A similar plenty of additional information also is found for the underlying soil classes (not shown) supplied to PROMET, that are important for the subsurface transport of temperature and moisture.

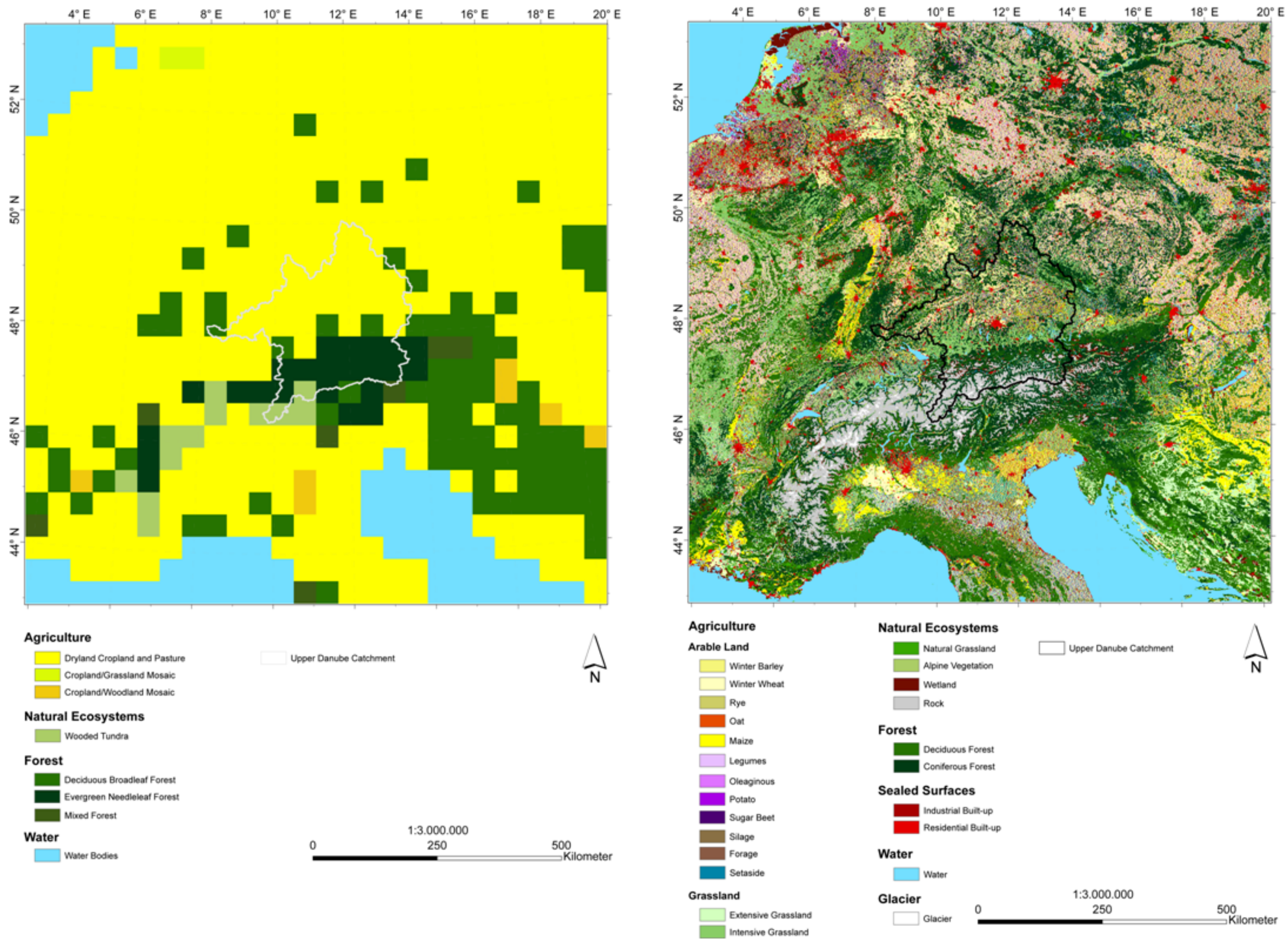


Figure 8.3: Landuse classification as used in MM5 intrinsic landsurface module at horizontal resolution of 45 km (left) and alternate dataset as seen by PROMET at a resolution of 1km (right) within area of interactive coupling

Technically the exchange of data in the coupling process is performed with the help of a directory visible to both, MM5 and PROMET. This special setup is necessary because MM5 is operated in a LINUX/UNIX environment, whereas PROMET depends on WINDOWS. To save data traffic only the coarse grid fields are exchanged and the scaling to the 1km resolution is done locally on the computer hosting PROMET. In this way a 'bottleneck' effect can be prevented. Ideally the coupling directory is realized within a virtual harddisk that resides in the main memory of the respective computer, allowing for high-performance access. The necessary upscaling of high resolution fields of PROMET is comparatively easy to perform by essentially aggregating corresponding areal means onto the 45 km grid of MM5.

The one way coupling of MM5 towards PROMET proves to be stable and reliable, producing realistic results concerning the regional hydrology, that by the way allows to assess the integrated performance of the driving meteorological fields, as has been shown in a previous chapter of this work. As an intermediate step to the full interactive coupling first of all the direction of the one way coupling is reversed similarly as has been described in the previous section on specific sensitivity tests. This is done such that pre-calculated data from PROMET are fed into the MM5 as time dependent lower boundary conditions. PROMET accordingly has been driven beforehand by MM5 for the corresponding period of time. It may be mentioned here that this approach is fairly similar to the method of one-way-coupling an ocean model to an atmospheric model. In doing so, the basic correctness and stability of the 'remaining' part of the two-way interactive coupling approach can be tested in a straightforward manner. Any drift possibly coming with the fully coupled mode and being hard to analyze thus is excluded. Early tests performed for the present study adopting this reversed one-way coupling revealed severe problems in the adaptation and mutual adjustment of the two models. This is illustrated by figure 8.4 showing accumulated precipitation for June 1996 as simulated by a control run with MM5's own landsurface module and a simulation of MM5 ingesting correspondingly prepared hourly PROMET data. First of all the inner part of the simulation domain where the coupling takes place shines through all too distinctly with generally enhanced rainfall amounts. Furthermore the maximum of precipitation is shifted from the Alps to a wide and oddly stretched area in the Alpine foreland. A closer analysis comparing the interactively coupled simulation with an independent MM5 control run and additionally with the surface data simulated 'online' in parallel, during the two-way coupled run by the NOAH-LSM, revealed unrealistic high discrepancies of surface heat fluxes. These results spurred considerable improvements within PROMET as, e.g., the implementation of a new and explicit approach of simulating the surface sensible heat flux. Furthermore, the exchange of the turbulence-scheme of MM5 from the Eta- to the MRF-PBL, as already mentioned above, that additionally was provided with the surface temperature for a consistent determination of the turbulence regime, allowed for considerably improved, highly realistic overall simulations presented in the following.

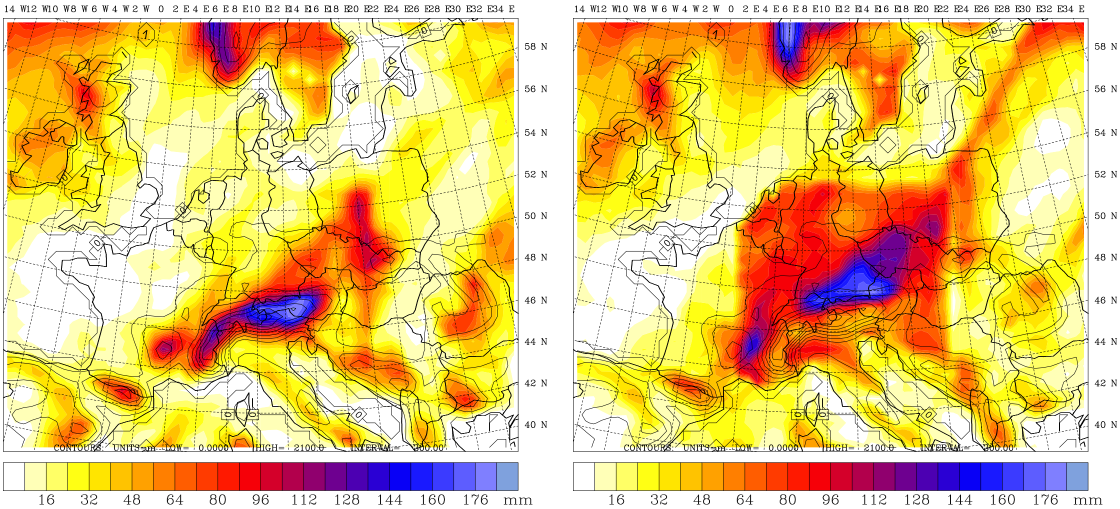


Figure 8.4: Precipitation simulated by MM5 for June 1996; control run with MM5 coupled to its own landsurface module (left), MM5 with hourly lower boundary data from pre-calculated, MM5-driven PROMET simulations (right). The PROMET coupling domain (cf. Fig. 8.3) in the inner part is (all too!) clearly discernible in the right panel

The interactively coupled test simulation of MM5 and PROMET so far comprises the years of 1996 to 1999. Due to the different formulations of the planetary boundary layer used for the reference simulation discussed in chapter 4 and the version in the setup of the interactive coupling to PROMET direct comparisons of the respective simulation results should be drawn only with some caution. The observational data shown for reference in the following are only available for the Upper Danube catchment. Thus, they differ somewhat from the observations employed in chapter 4. In fact they are the same that are used to drive PROMET for the evaluation of MM5 simulations under hydrological aspects in chapter 6.

Figure 8.5 depicts mean annual precipitation for the four years simulated by MM5 with the NOAH-LSM and PROMET, respectively. The overall patterns are quite similar showing realistic features such as precipitation maxima in the upslope areas in the north and west of the Alps. Simulated fields of MM5/PROMET show smooth transitions at the boundaries of the PROMET domain. Thus, boundary artifacts such as found in Fig. 8.4 are no longer discernible. The areal difference signal evaluated at the native resolution of MM5 of 45 km predominantly shows an overall decrease of precipitation amounts particularly in the south of the Alps. The areal means in the Upper Danube catchment sum up to 1180 mm with the NOAH-LSM compared to 1095 mm with PROMET, the latter thus being somewhat closer to the observed value of 1045 mm. The annual sums are complemented by the mean annual cycle of monthly values presented in figure 8.6. Generally the observations are well represented by the simulations showing the familiar maximum in summer and lowest precipitation in winter. The simulations reveal a clear trend to an overestimation of precipitation in the colder seasons, whereas in summer also underprediction occurs. Winterly overprediction of precipitation, however, should be seen in context of possible undercatchment in observations in mountainous terrain, as has already been discussed in chapter 4. Apart from November MM5/PROMET more or less distinctly simulates less precipitation than MM5/NOAH, thus attenuating the predominant tendency to overprediction of the standard MM5. In July and September, however, this entails an even somewhat aggravated underprediction. Nonetheless PROMET on balance leads to a better performance of the overall simulations compared to the NOAH-LSM.

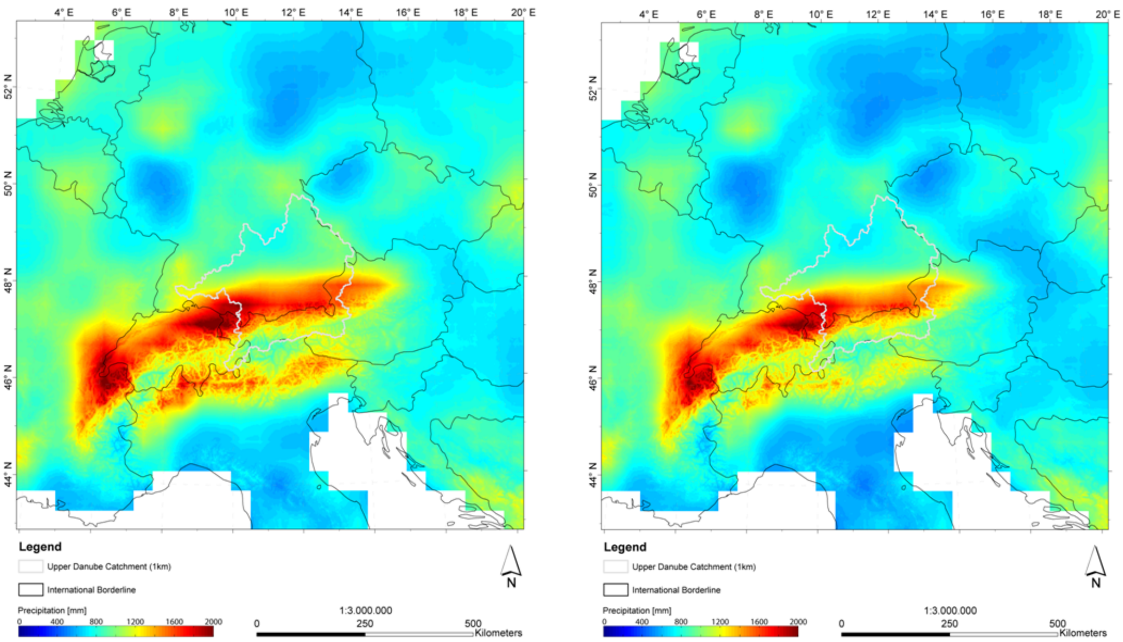
The results in respect of simulated temperature patterns are presented in figure 8.7. MM5/PROMET predominantly simulates higher near surface temperatures with the exception of higher Alpine areas and some mountainous areas in Italy and former Yugoslavia. The overall cold bias in the Upper Danube catchment simulated by MM5/NOAH resulting in a mean value of 5.9 °C, compared to observed 6.8 °C, thus is almost made up for by switching to PROMET with its 6.7 °C. These differences can be traced back to altered annual mean surface heat fluxes depicted in figure 8.8. Here a discernable predominant increase of the sensible heat flux for the whole area north of the Alps gets obvious, accompanied by prevailing decrease of latent heat flux. The areal means of sensible heat flux result to 14.2 W/m^2 for MM5/NOAH compared to 15.3 W/m^2 for MM5/PROMET, and 35.9 W/m^2 and 29.8 W/m^2 for latent heat flux, respectively. For reference also the values for the 1-way coupled PROMET are shown emphasizing the influence of feedback effects in the coupling of atmosphere and landsurface especially with respect to sensible heat flux featuring an even significantly higher value of 17.5 W/m^2. The annual cycle of mean monthly temperatures, averaged over the Upper Danube catchment, (figure 8.9) reveals that a major contribution to the annual cold bias of MM5/NOAH can be ascribed to too low simulated temperatures in summer. Implementing PROMET raises temperatures up to 1.5 K in the warmer season, whereas practically no effect can be noticed from December to April. Obviously, improvements concerning temperature are only to be accomplished in conjunction with an activated vegetation. Figure 8.10 zooms into the mean diurnal cycle for June and December. For June the cold bias is strikingly reduced by an overall shift of about 1.5 K resulting in a virtually perfect agreement during night-time and almost until noon. The bias in the afternoon, however, persists as noticed and discussed for the reference simulation of chapter 4. (Again, the comparison of results presented here to the results of chapter 4 should not be pushed too far as model configurations, observational datasets and the respective time periods are somewhat different.) For December no significant differences can be found between the two simulations. Thus, the discrepancies to observations in winter, when vegetation is at rest, should be due to other aspects of the simulation, apart from the atmosphere-landsurface coupling. It may also be mentioned here that the years 1996 to 1999 originally where chosen as being representative for the 1990ies with respect to precipitation—the variable being in the very focus of the whole

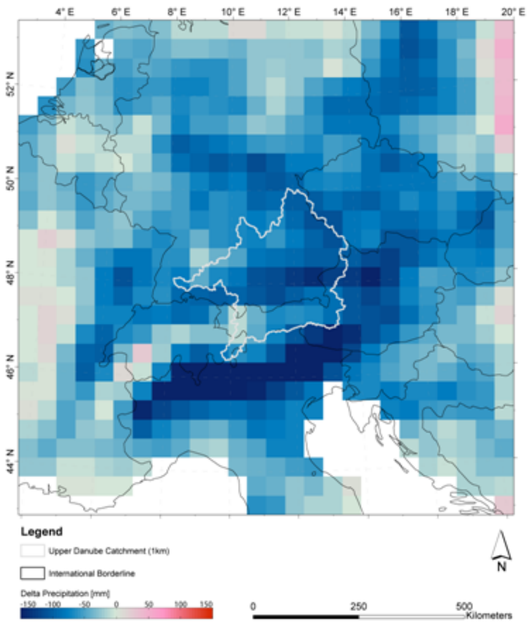
GLOWA-Danube project.

8.4 Summary and Discussion

MM5 comes already with a comparatively elaborate and mature landsurface-vegetation module (the so-called NOAH-LSM). This allows for simulations on climatological time-scales. Here, the interactive feedbacks between the atmosphere and a time dependent lower boundary, particularly reproducing a realistic annual cycle of the activity of plants, are essential. The performance of this standard setup was validated, for example, in chapter 4, where a long-time reference simulation conducted with MM5 was presented, with simulated precipitation and near surface temperature comparing very well with observations in the upper Danube area. Furthermore, simulations performed with the sophisticated landsurface-vegetation-hydrology model PROMET, driven in a one-way mode with MM5 output, resulted in quite realistic annual cycles of mean monthly discharge values (cf. chapter 6). There is, however, and as ever, still room for improvement. Thus, it seems somehow obvious to aim at taking advantage, also in the view of the meteorological simulation, from the high sophistication of PROMET, well exceeding the corresponding capabilities of the original MM5 scheme. PROMET has available high-resolution datasets of soil, landuse and vegetation types that include highly differentiated parameter sets for a large variety of plants. In addition it relies on sophisticated formulations on plant physiology, concerning e.g. photosynthesis and stomatal resistance, governing particularly the process of evapotranspiration and thus the surface fluxes of latent and sensible heat of vegetated areas. Last but not least it can be operated at a considerably high horizontal resolution of 1 km, allowing for a highly realistic simulation of the various relevant processes.

The two-way coupling of both, MM5 and PROMET, had to be performed, such as to replace the original landsurface/vegetation scheme of MM5 with PROMET. Accordingly, first of all, surface fluxes of sensible and latent heat and of momentum, as well as upward radiation, simulated by PROMET, have to be fed into the lowest atmospheric level of MM5. Furthermore, also the ground temperature had to be included into the set of coupling variables to assess consistently the respective atmospheric stability in the boundary layer. Preparatory tests revealed some delicate sensitivities concerning particularly the surface heat fluxes and their relative proportions. Moreover, the time step of the coupling, that originally was set to 60 minutes in the overall GLOWA-Danube simulation system, turned out, naturally, to be inappropriate in view of an interactively coupled meteorological model and was changed to 10 minutes. First truly interactive simulations of the coupled system resulted in substantial overprediction and unrealistic patterns of precipitation. A closer analysis revealed differences in simulated surface fluxes between PROMET and the NOAH-LSM that were way beyond what had to be expected due to the different formulations of both models. These findings necessitated a comprehensive redesign, including an explicit simulation of the sensible heat





MM5+	NOAH	PROMET	Obs
Upper Danube	1180	1095	1045

Figure 8.5: Mean annual precipitation of the years of 1996 to 1999 as simulated by MM5 with its own landsurface module (upper left) and interactively coupled to PROMET (upper right), downscaled to 1km. Lower panel: difference between MM5/NOAH and MM5/PROMET at native resolution of MM5, table: mean annual sum of precipitation [mm] as simulated and observed in Upper Danube catchment (indicated by white outline). Artifacts at the boundaries of the PROMET domain, such as found in the overall domain in Fig. 8.4, are no longer present

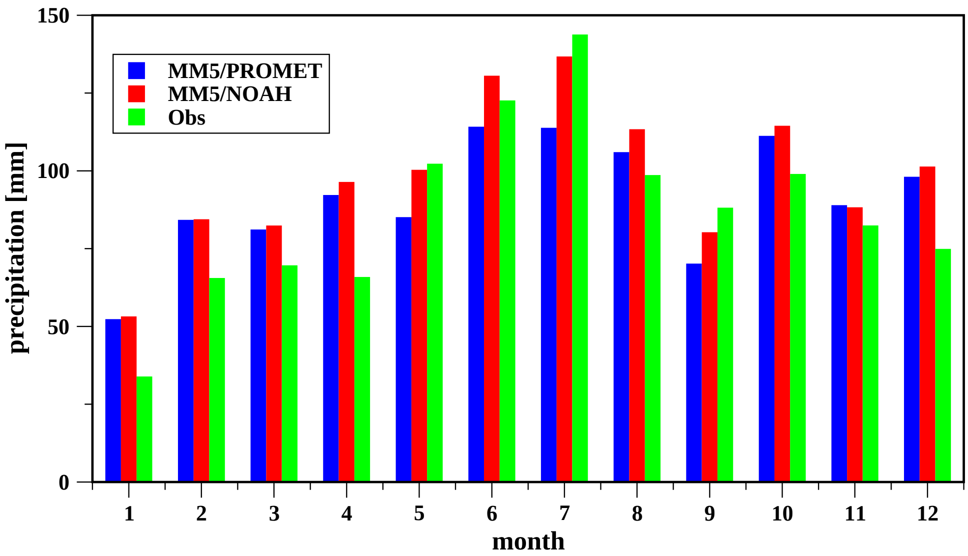
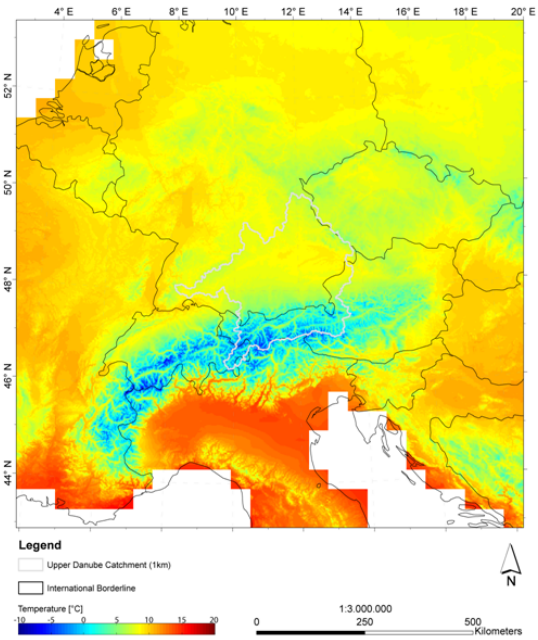
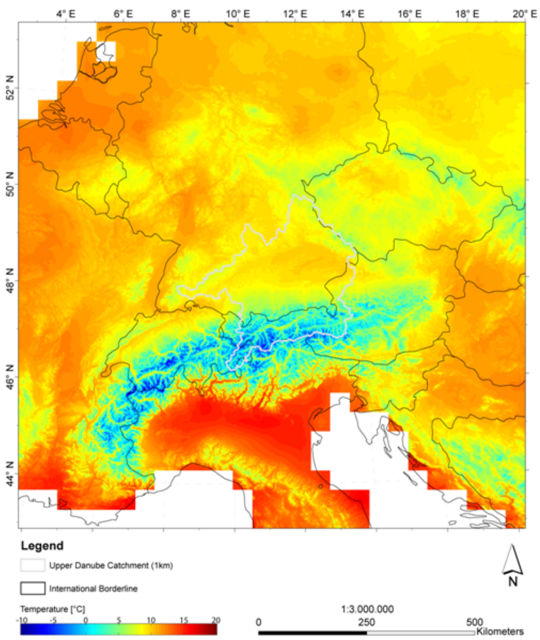


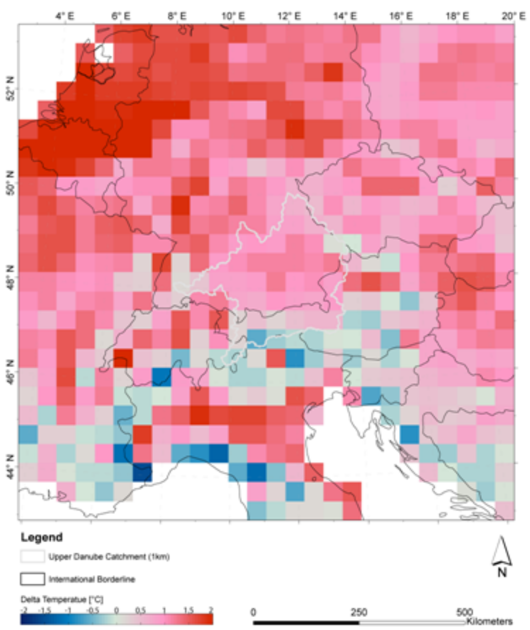
Figure 8.6: Mean monthly precipitation of the years of 1996 to 1999 as simulated by MM5 interactively coupled to PROMET ('MM5/PROMET') and with its own land-surface module ('MM5/NOAH') versus observations ('Obs')

flux (implemented into PROMET by the GLOWA-Danube hydrology group), that so far had been calculated as a residuum, and the replacement of the planetary boundary scheme, as well as the already mentioned implementation of a consistent determination of low level atmospheric stability. These considerable efforts were rewarded by considerably improved simulations of the interactively coupled system of a four year period (1996–1999), that allowed for more realistic results, compared to MM5/NOAH-LSM, concerning the key variables precipitation and near surface temperature in the upper Danube catchment. The characteristic pattern of mean annual precipitation now is reproduced very well, with precipitation maxima in the upslope areas of the Alps corresponding to the predominant flow from north-westerly directions. The slight positive bias of 13 % in the area of interest for MM5/NOAH is reduced to about 5 %, whereas the annual cycle is captured quite realistically with mean monthly values generally closer to observations. Concerning near surface temperature the overall annual cold bias of MM5/NOAH is rectified almost perfectly with MM5/PROMET, which is related to a higher mean value of sensible heat flux (+1 W/m^2 or +8 %). The latent heat flux on the other hand is reduced by -17 % (-6 W/m^2) indicating too much evapotranspiration simulated with the NOAH-LSM. Furthermore, the analysis of the annual cycle of mean monthly temperatures as well as the comparison of mean diurnal cycles of temperature for June and December show substantial improvements only for the warmer season. Hence, the improved performance obviously is due to PROMET's more sophisticated parameter database and the formulations concerning (an active) vegetation.

All in all the fully two-way coupled modelling system MM5–PROMET builds a robust basis for further research within follow-up projects of GLOWA-Danube. It will

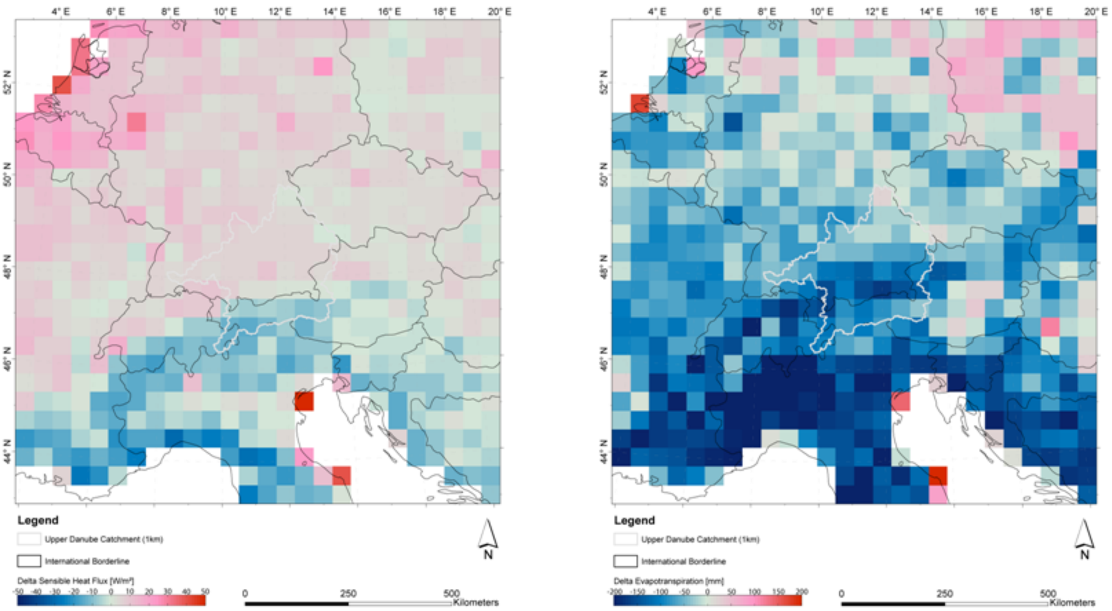






MM5+	NOAH	PROMET	Obs
Upper Danube	5.9	6.7	6.8

Figure 8.7: Mean annual temperature of the years of 1996 to 1999 as simulated by MM5 with its own landsurface module (upper left) and interactively coupled to PROMET (upper right), downscaled to 1km. Lower panel: difference between MM5/NOAH and MM5/PROMET at native resolution of MM5, table: mean annual temperature [°C] as simulated and observed in Upper Danube catchment (indicated by white outline)



MM5+	NOAH	PROM-1way	PROM-2way
sens. heat	14.2	17.5	15.3
lat. heat	35.9	29.2	29.8

Figure 8.8: Difference between mean annual sensible (left) and latent (right) heat flux as simulated by MM5's own NOAH-landsurface module and by PROMET interactively coupled to MM5 ('PROMET' - 'NOAH', 1996-1999), table: areal means of surface fluxes $[W/m^2]$, for comparison also with 1-way coupled PROMET

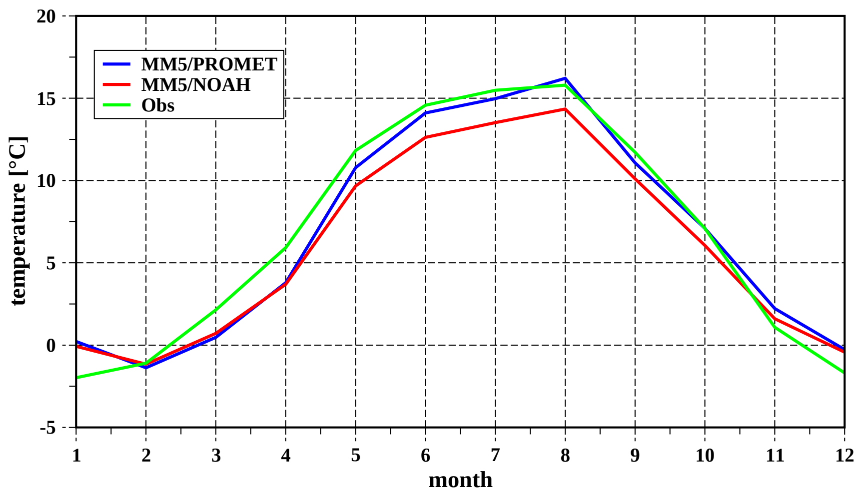


Figure 8.9: Annual cycle of mean monthly near surface temperature in upper Danube catchment of the years of 1996 to 1999 as simulated by MM5 interactively coupled to PROMET ('MM5/PROMET') and with its own landsurface module ('MM5/NOAH') versus observations ('Obs')

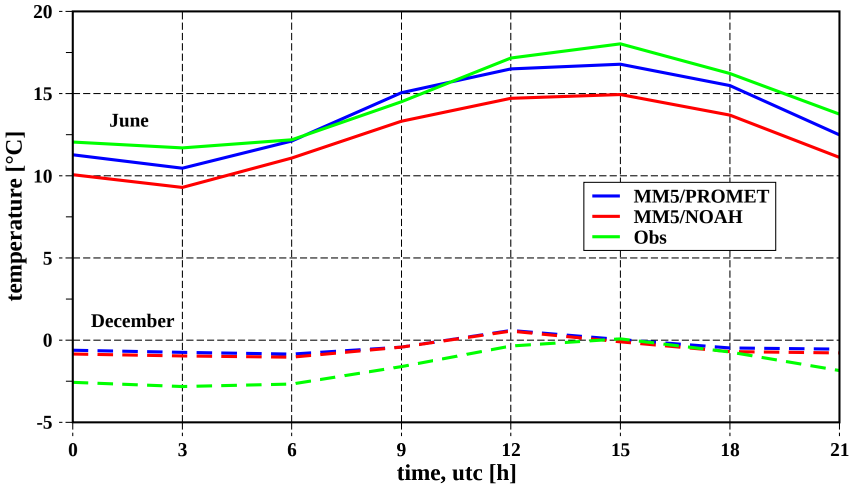


Figure 8.10: Mean diurnal cycle of near surface temperature (3-hourly, UTC, areal mean of upper Danube catchment) for June and December of the years of 1996 to 1999 as simulated by MM5 with its own landsurface module ('MM5/NOAH') and interactively coupled to PROMET ('MM5/PROMET') vs. observations ('Obs')

allow for the full integration of regional feedback effects of the underlying surface and particularly its vegetation onto regional climate simulations. Thus, the last goal of this thesis, i.e. to fully integrate MM5 into the overall modelling system, that was envisioned as one of the major goals of GLOWA-Danube, could be achieved successfully.[1]

[1]Concepts and findings of this chapter are also presented in Zabel et al. 2011 and in Mauser et al. 2010

Chapter 9

Summary, Conclusions and Outlook

In the first section of this chapter the results of this thesis will be summarized, assessed and concluded. The second and last section will suggest some promising starting points for further research tying in with the findings of the present study.

9.1 Summary and Conclusions

The ultimate overall goal of the original working package underlying this thesis was to provide highly realistic regional climate datasets for the use within the interdisciplinary GLOWA-Danube project and its subsequent climate impact models on a substantially high horizontal resolution of 1 km. Additionally, a regional climate model had to be coupled in a fully two-way interactive mode to a landsurface/vegetation model, contributed by the hydrology group of the project. Accordingly this working package was broken down to a set of five single 'milestones', as outlined in the introduction, that were met within this dissertation, bringing about valuable new insights and methods, as summarized in the following.

Identification of the appropriate configuration of MM5 The first aim of this study was to investigate the applicability of MM5, driven by the observation based ERA40 reanalysis dataset, as a regional climate model in the Alpine area and to conduct a long time simulation as a reference experiment for further regional climate studies in the future. A set of sensitivity experiments was analyzed that, on the one hand, gave an idea of the 'intrinsic' range of simulation results for precipitation inherent to the MM5-system. This was done by using three different convection parameterization schemes. On the other hand this range of simulation results also gave a frame of reference to assess the influence of the formulation of the numerical horizontal diffusion on simulated precipitation.

Validation was focussed primarily on precipitation, and in the case of the reference experiment additionally on near surface temperature and dew point temperature. Verification of simulated precipitation is quite problematic in principle due to the lack of reliable unbiased observation data. So the observational basis was broadened by using two different datasets. One was built from spatial averages of raw station data and the other was constructed with the help of a high-resolution climatology of precipitation for the Alpine area.

The set of sensitivity experiments was performed for the four-year period from 1996 to 1999 that proved to be representative for the 1990s. The simulations generally were confined to a moderate resolution of 45 km as the computational resources dedicated to MM5 in the complex overall coupled scenario simulations within the GLOWA-Danube project are quite limited. The main findings, however, should not be affected significantly by this choice of resolution. The basic model setup used was identified by a set of preparatory test simulations as being optimal for the specific purpose. Three widely used convection parameterizations have been compared with respect to simulated rainfall amounts—the schemes known in the MM5 as Grell, Betts-Miller and Kain-Fritsch-2 scheme. Together with two different ways to implement numerical horizontal diffusion, namely σ-diffusion formulated along terrain-following model levels and the truly horizontal z-diffusion, an 'ensemble' was spanned with six different simulations. Depending on the combination of the cumulus convection scheme and the option for numerical horizontal diffusion very large differences were obtained in simulated precipitation that became obvious particularly, as had to be expected, in the summer season. The simulation bias ranged (somewhat depending on the observational dataset) from an overprediction in summer of up to 270 mm in the higher Alpine region using the Betts-Miller scheme together with σ-diffusion to a deficit in rainfall of about -140 mm when combining the Grell scheme with truly horizontal diffusion. The Betts-Miller-scheme seems to be least suitable for mountainous terrain with a tendency for overprediction near mountain tops even with z-diffusion whilst the Grell-scheme shows substantial negative biases in any case. Implementing the optimal combination (with respect to the purposes of GLOWA-Danube), i.e. the Kain-Fritsch-2 scheme together with truly horizontal diffusion, eventually reduced bias and other error scores to a minimum that is of the same order as the range of observational uncertainty. It may be worth noting that the effect (with respect to simulated rainfall amounts) of replacing the Betts-Miller- with the Kain-Fritsch-2 scheme brings about almost the same improvement as switching from σ- to z-diffusion (cf. third row in Fig. 4.2).

The unphysical upslope transport of moisture brought about by formulating diffusion along terrain-following model levels generally resulted in a systematic mislocation of simulated precipitation between the Alpine foreland and the Alps, shifting the maximum to mountain tops. Simmons (1986) as well as Giorgi (1991) suspected this side effect of σ-diffusion, entailing excessive simulated precipitation in mountainous areas, already about two decades ago. A closer inspection or systematic rectification of this issue, however, obviously has not taken place since. Thus, the analysis performed in the framework of this thesis helped to tackle a long-standing issue of simulating precipitation in mountainous terrain, that was sort of hidden a little deeper in the numerics.

The direct comparison of σ- vs. z-diffusion in context of precipitation in complex orography, that was obviously performed for the first time systematically in the present (RCM-)study, brought about some quite impressive results, that are highly relevant for other researchers and corresponding studies. In the view of these results it is highly advisable for studies with comparable mountainous simulation domains to substitute terrain-following horizontal diffusion with schemes that do not entail substantial vertical transport of, first of all, moisture. This is achieved in a most straightforward manner by truly horizontal z-diffusion. In MM5 this option is already implemented as an alternative to the 'traditional' σ-diffusion. For other models, however, this convenient provision might not be given. Thus, other approaches might follow Simmons (1986), who suggests to apply σ-diffusion, if possible, to appropriately defined variables that are more or less uniformly distributed in the vertical, or to implement correction terms following respective reference profiles of the variables to be diffused. Jacob and Podzun (1997) accordingly introduced correction terms in the horizontal diffusion of momentum, temperature and moisture. Jacob (2001) and Jacob et al. (2007), however, still get overprediction of precipitation in the convectively dominated seasons of spring and summer in the (partly mountainous) drainage basin of the Baltic Sea and in the Alpine area, respectively. This finding possibly indicates, that trying to solve this issue with correction terms might only be the second best solution.

Switching to truly horizontal z-diffusion also might help most conveniently to improve a variety of studies such as that of Fernández et al. (2007), who found excessive precipitation amounts simulated with MM5 over mountainous areas of the Iberian Peninsula, particularly in summer. Based on the findings of the present study it can be expected, that z-diffusion most probably would lead to much more realistic fields of simulated precipitation especially in the elevated areas of their simulation domain. Besides that their findings generally agree well with the results of the sensitivity experiments of the present work concerning the convective parameterization, with the Kain-Fritsch scheme producing systematically more rain compared to the Grell scheme.

The reference experiment, relying on the optimal configuration identified, was conducted for 10 years from 1991 to 2000 driven again with ECMWF's ERA40 reanalysis data. Verification of simulated precipitation still showed some deficiencies especially in the higher Alpine regions, the extent of which depends on the observational dataset considered. In general, however, the simulation results compare quite well to the range spanned by the two observational datasets and therefore give a reasonable basis and reference for any subsequent regional impact studies in the area of interest. Validation of temperature was restricted more or less to the Alpine foreland for practical reasons. The mean diurnal cycle of near surface temperature for each month was also simulated quite realistically, showing however some cold bias of up to 2 K mainly in the afternoon hours of the warmer seasons and some warm bias in wintertime morning hours—a finding also reported for other regional models (Hohenegger et al. 2008, Fernández et al. 2007). The near surface dew point temperature, i.e. the moisture budget near ground, is also captured quite well by the model but still shows some deficiencies in the afternoon with an overprediction of up to 2 K.

The first part of the present study shows quite impressively that models and parameterizations developed for certain specific applications and areas (e.g. simulation of tropical convection over oceans) and giving reliable results there, have to be critically re-evaluated if applied to a completely different region of the world. While the Betts-Miller-scheme is used quite successfully for other regions of the world (Kerkhoven et al. 2006) it does not seem to be properly adapted to the Alpine region. Furthermore, models that have been developed for the use at quite coarse horizontal resolutions—mainly due to restrictions in available computer resources—cannot simply be run unaltered on finer grids as soon as computer technology allows for that. For example, the formulation of horizontal numerical diffusion along terrain following coordinates is quite effective and appropriate as long as a model is run at a coarse horizontal resolution or over marginally structured terrain without any steep valleys or mountains. Refining the grid even only moderately in an area with complex orography like in the upper Danube area, where the model layers can be tilted substantially, this inevitably leads to unrealistic simulation results as now a hitherto 'good-natured' scheme suddenly brings about unphysical processes.

Overall, an optimized configuration of MM5, in view of the key variables precipitation and near surface temperature, for the purpose of regional climate modelling in the upper Danube Catchment could be identified. This was done by taking advantage of the numerous options of the MM5 modelling system while at the same time avoiding to get lost in its manifold possibilities. Thus, the first objective of the current thesis was achieved successfully.

Analysis of MM5 simulations driven with ECHAM5 output The second objective of the present thesis is dedicated to the validation of the regional climate simulation approach in the Alpine area focussing on the impact of the large scale flow, given by the driving model, on simulated precipitation. To do so long term simulations for the years of 1971 to 2000 of the regional climate over Western Europe were performed using MM5 as regional model on a 45-km grid that was driven either by the 'quasi-observational' ERA40 data set or by the global circulation model ECHAM5.

The simulated 30-year MM5-ERA40 climatology of precipitation compares quite satisfactorily with an observational climatology compiled by Frei and Schär (1998) for the Alpine region. An important reason for choosing the Alpine area for validation is that simulated precipitation there reacts particularly sensitively to any inaccuracies in the chain of the simulation models. Switching to ECHAM5 as the driving GCM turned out to induce a massive overprediction of mean monthly precipitation sums in the colder seasons. The seasonal patterns correspondingly revealed excessive amounts in mountainous upslope areas of the Alps and the Apennine. In the Alps the MM5-ECHAM5 climatology reached values exceeding the quite realistic MM5-ERA40 simulations (cf. chapter 4, Pfeiffer and Zängl 2010) in winter by up to 80 % and also the Alpine foreland features a considerable surplus amount of precipitation.

The source of these drastically altered rainfall regimes was found to lie in relatively moderate differences in the large scale circulation provided by the global data sets. This was corroborated first by seasonally averaged sea level pressure fields. Particularly in winter, noticeable differences were found between the driving input data that essentially prescribe the large scale flow conditions for the regional model. A slight southward shift of the winterly mean low pressure over the Atlantic and the reorientation of mean isobars in central Europe indicate an increase in the number and/or an intensification of low pressure systems travelling from the Atlantic into the Alpine area found for ECHAM5 compared to the situation under the more realistic ERA40 climatology. The underprediction of summertime rainfall south of the Alps and over the Mediterranean part of the analysis domain on the other hand is connected to a somewhat higher pressure here. Mean seasonal wind speeds in the Alpine area at a level of 700 hPa showed higher values in all seasons for MM5-ECHAM5 in accordance with more closely spaced isobars reaching into south Germany. In winter averaged 700 hPa wind speeds of around 16 m/s were reached in the central Alps compared to 12 m/s with MM5-ERA40.

Three-hourly aggregated 700 hPa winds in the central Alps, partitioned according to wind direction and wind speed, revealed the expected maximum for westerly winds in the MM5-ERA40 climatology. The number of wind events here clearly decreases from lower towards higher wind speeds. Switching to ECHAM5 strikingly overweighs higher wind speeds particularly for westerly directions in winter in accordance with the findings for sea level pressure and mean seasonal wind speeds. As demonstrated by partitioning the individual rainfall amounts of all 3-hourly rainfall events to the same wind direction and wind speed bins as in the case of the wind statistics the shift towards higher wind speeds in the MM5-ECHAM5 case indeed explains the excessive wintertime precipitation in the Alpine region.

All in all these results give reason to some concern about the significance and usability of current regional climate modelling with respect to simulated precipitation in areas of complex orography. The direct use of these data in subsequent climate impact research in many cases is not a viable option as long as the driving GCMs show the deficits discussed here. Although the overall large scale deficits are quite small the 'downstream' effects in the regional model, first of all on the very sensitive rain generation processes, get substantial locally, i.e. in the Alpine area. It has to be kept in mind here that whilst the ERA40 analysis model and the ECHAM5 model are quite similar in their formulations and so might be expected to produce generally similar results, both models have to face substantially different tasks. The 'ERA40-model' is continuously fed with a vast amount of observation data and so will always be nudged back to reality. The ECHAM5 model as any other GCM, however, is largely free in finding its solutions and is only bound to a small number of external forcings like e.g. the orbital parameters of the Earth and thus the incoming solar radiation. In the view of these circumstances the ECHAM5 is actually doing remarkably well by e.g. shifting the main track of low pressure systems in winter only about 500 km too far south (cf. fig. 5.4), reflecting the great progress that has been made in GCMs for about the last twenty years.

In the framework of the PRUDENCE project Jacob et al. (2007) evaluate the performance of several RCMs driven by a GCM under present day climate conditions. Beforehand they identify discrepancies in terms of large scale mean sea level pressure between ERA40 and their driving GCM (HadAM3, Pope 2000). These discrepancies are similar to those between ERA40 and ECHAM5 (see above) and thus gives them at least some clue to the origin of the overprediction (compared to observations) of their simulated precipitation, first of all in winter. However, Jacob et al. (2007) omit to conduct corresponding RCM-simulations driven by ERA40 data to allow for a detailed analysis of the exact impact of the altered large scale forcing on the regional model simulations. GCM-RCM generated data are quite promising (Jacob et al. 2007), but they are not (yet?!) perfect—the specific deficiencies should nonetheless be identified thoroughly to avoid inappropriate conclusions drawn from 'climate change signals' deduced from such simulations, but rather to 'mark' such projections with a certain 'level of confidence'.

A lesson to be learned from the present study in this context is, that RCM studies, aimed at the investigation of climate change, should always include simulation runs that are driven by observation based re-analysis data for reference. This, naturally, leads to substantially higher costs (first of all with respect to computational resources). Costs, however, that are well justified as they allow eventually for a comprehensive and systematical evaluation of the GCM-RCM chain in question, and hence as well for a more conclusive assessment (in terms of validity and robustness) of corresponding studies on future climate change. Furthermore, these additional (reanalysis–RCM-) simulation data can be used to directly assess the relative effects of GCM-RCM simulation biases in respective downstream impact modelling and, if applied, the validity of a bias correction here (cf. chapter 6 and next section below). Moreover, the data gathered by re-analysis driven RCM simulations might serve as a rough basis for subsequent bias correction on the RCM scale for climate change runs, if corresponding climatological observation data are not available for the respective research area.

Overall, the second objective of this thesis, i.e. to analyze the nested model approach in view of the driving GCM, was accomplished successfully such as to clearly identify the reasons for deficiencies in simulated precipitation. Whilst the RCM used performs quite realistically in the Alpine area, when nested in an observation based meteorological environment, GCMs still exhibit seemingly minor but non-negligible shortcomings in the context of subsequent regional climate modelling. Performing global simulations and improving GCMs, however, apparently is way beyond the scope of this thesis.

Naturally, there is no other 'clean' way to correct for intrinsic errors of the GCM than to find the appropriate formulations of equations and parameterizations. A subsequent RCM cannot systematically correct for systematic large scale errors imposed by the driving GCM. Still, regional climate modelling is a valid concept even in complex terrain. As a working solution to overcome the current deficiences in simulated rainfall a systematic bias correction is suggested and analyzed in chapter 6 that is summarized in the following.

Statistical downscaling of MM5 output and overall performance of meteorological simulations in view of downstream hydrological simulations The preparation of high-resolution (1 km) regional climate datasets for present day conditions as well as for a future climate scenario is essential for the project GLOWA-Danube. Due to various reasons outlined in the introduction of this thesis it was not only desirable but indispensable to resort to the implementation of a regional climate model. It was, however, not feasible to conduct the necessary simulations, extending all in all over about 130 years, at the extremely high target resolution. Thus, an additional subsequent, very cost-effective statistically based downscaling technique has been devised in the course of the project.

The third aim of the present thesis accordingly was to refine the statistical downscaling for the actual and practical use within GLOWA-Danube and to analyze the performance of the resulting combined, dynamical and statistical, downscaling technique in the view of downstream hydrological modelling.

The resulting new overall downscaling approach combines the advantages of both, dynamical as well as statistical downscaling. On the one hand it allows for consistent datasets of the meteorological variables, required by the subsequent impact models, that are linked to regional feedbacks of, for example, the underlying landsurface and vegetation. On the other hand, the use of an additional statistical approach helps to reduce the demand for computational resources and thus allows for an 'on-line' implementation of the all-up meteorological downscaling into the overall simulation system of GLOWA-Danube. Furthermore, as the statistical downscaling is based on empirical relations between observed and simulated climatologies, an additional option for a bias correction is easily included into the corresponding algorithm. The bias correction is essential particularly if the chain of regional downscaling is driven by GCM input, that entails substantial overprediction of precipitation in the colder seasons (cf. chapter 5). Without bias correction any subsequent hydrological simulations would be unfeasible or meaningless.

The basic concept of the statistical downscaling consists in the intercomparison of a high resolution (1 km) observational climatology in the area of interest and a corresponding coarse resolution simulated climatology. Both climatologies are effectively related to each other, on a mean monthly basis, most straightforward by essentially computing the quotient of both fields on the high resolution grid. This results in a set of monthly fine scale factor fields that may be interpolated in time to give daily values. Thus, the observed fine scale variability of, e.g., precipitation, that cannot be captured in principle by the coarse-resolution regional model (in this case 45 km), can be impressed 'ex post' onto corresponding regional simulations. This is done by a simple multiplication of the simulated coarse scale fields with the fine scale factor fields gathered before in a training period. This approach includes a bias correction by construction, as any bias appears in the factor fields at the original coarse scale of the regional model. To avoid harsh discontinuities the coarse scale regional simulations generally should be bilinearly interpolated onto the fine grid. To switch off the bias correction the observed climatology has to be compared in a way with itself, by artificially reducing its resolution to the coarse scale and then to compute the corresponding quotients between fine scale and coarse scale observation climatology. This, naturally, is only advisable if no substantial bias exists in the simulations to be downscaled later on.

This technique can also be applied to other variables as long as suffient observational high-resolution data on climatological timescales are available. For temperature the approach has been modified such as to simply replace all divisions and multiplications with corresponding calculations of differences in the intercomparison of climatologies as well as summations in the application of scaling functions onto 'operational' simulation results. This corresponds more appropriately to the nature of the quite systematic (i.e. first-order linear) relation between temperature and orography height, essentially underlying the downscaling problem for this variable. The downscaling of surface pressure was converted during the course of this thesis from the original multiplicative approach to one making use of the barometric formula.

The overall meteorological model chain, from global and regional model to statistically based downscaling, had to prove its suitability from the view of subsequent hydrological (impact) modelling. Accordingly, simulation output from this chain for present day climate conditions (for the years 1972–2000) has been fed into the hydrological model PROMET (Mauser and Bach 2009) in cooperation with GLOWA-Danube's hydrology group to simulate mean monthly discharge values of the upper Danube catchment. Furthermore, also statistics of daily discharge amounts were considered. This has been done under ERA40 as well as ECHAM5 global meteorological conditions. In particular, simulations with and without adopting a bias correction as described above were performed. This revealed clearly that a bias correction is indispensable under global input provided by ECHAM5 (and presumably any other current global climate model). This is due to the massive overprediction of precipitation simulated by the nested regional model in the colder season (cf. Jacob et al. 2007), that inevitably gets reflected in an overprediction of subsequently simulated mean monthly discharge as well as in daily discharge spectra shifted towards substantially higher values. The bias correction acting upon the RCM output effectively adjusts the overall overprediction in the downstream hydrological model, leaving only a time shift in the annual cycle of the mean monthly discharge, with the maximum shifted from June/July to May (cf. Fig. 6.4). This timing issue points to highly intricate non-linearities of subscale processes in a highly structured mountainous orography, relevant for regional hydrology and particularly connected to the onset of snowmelt (Strasser 2008, Bernhardt 2010).

All in all the evaluation in view of subsequent hydrology corroborated quite impressively the validity of the overall meteorological modelling approach discussed in this dissertation. Without the investigations performed in chapter 6 the concept of treating substantially biased GCM-RCM simulations with a subsequent correction would have remained debatable to some extent. In this context it again proved quite valuable to perform re-analysis driven simulations as well. The evaluation of the ERA40-MM5 results in view of hydrological modelling allowed on the one hand for a clear assessment of the general potential of the 'ideal' regional climate simulation approach, i.e. with a 'perfect' GCM. On the other hand the basic relevance and efficiency of the bias correction technique could be demonstrated. These additional informations on the potential accuracy in view of impact research was highly relevant for the overall GLOWA-Danube project.

The present work complies well to the increasing request for integrated 'end-to-end' regional climate research, directly testing downscaling approaches together with downstream impact models in contrast to isolated studies (Leung et al. 2003). This request has been renewed by Fowler et al. (2007) particularly for hydrological studies. Furthermore, Leung et al. (2003) suspect driving GCMs as the major source of uncertainties—an issue that was systematically investigated and confirmed within the present dissertation for the overall model chain in close cooperation with GLOWA-Danubes hydrologists. The resulting need for a bias correction was as well identified by Fowler et al. (2007) in their review on various downscaling techniques.

Whereas Salathé et al. (2007) first of all resort to statistical downscaling for their study on climate change and its impacts on hydrology in the Pacific Northwest of the United States, they also perform a reference study using a RCM. They find systematic shortcomings of statistical downscaling that, other than physical-dynamical downscaling, in principle is not capable to capture relevant local processes and responses such as those leading, in their area of interest, to reduced snow cover, increased cloudiness and an altered radiation budget, eventually resulting in locally enhanced warming. A RCM, however, although admittedly superior in some respect, is judged by them as computationally too expensive. Fowler et al. (2007) see statistical and dynamical downscaling as two separate techniques with specific pros and cons. In the sense of

Hewitson and Crane (2006) cost-effective statistical downscaling could be used to give 'first-order-responses' of regional climate to whole ensembles of global change simulations. Upon the identification, using empirical-statistical methods, of the most relevant or scientifically most interesting candidates (in view of regional impacts) of these global scenarios the corresponding GCM simulations can be used to drive regional models as 'higher order methods' to incorporate relevant feedback effects and thus to reveal additional processes and details. The approach devised for GLOWA-Danube, refined and applied within this study, in a way goes beyond that separation of both downscaling techniques and effectively merges both methods. Additionally, the specific statistical downscaling approach used here includes a bias correction as discussed above. The underlying approach of this bias correction is in accordance with Themessl et al. (2010), who performed a study on statistical downscaling in the Alpine area. They recommend methods that base on calibrations of RCM simulations driven by GCM control runs, which is already fulfilled here.

The notion, that the bias correction implemented in this study in any case will adjust the subsequently simulated annual discharge values, is refuted by an analogous experiment based on a different regional model named REMO (Jacob and Podzun 1997). Here, the downscaling and bias correction was implemented in an identical manner. The excellent results in the view of downstream simulations of hydrology, achieved with MM5, could, however, not be reproduced with REMO (cf. Marke et al. 2009, 2010, 2011). The bias correction according to climatologies of mean monthly values still allows for each regional models very own temporal variability. Thus, it has to be kept in mind, that any particular simulation is performed in a fully dynamical mode, with input to the hydrological model on an hourly basis, potentially resulting in quite different pathways of the simulated system for different (climatology-based bias-corrected) RCMs. The careful evaluation and optimization of MM5 (cf. chapter 4) hence prove to be worth the effort also in the context of downstream hydrology.

Thus, all in all the third goal of this thesis could be achieved successfully, such as to refine the statistical downscaling approach, to apply it in subsequent hydrological modelling and to evaluate the overall performance of the whole meterological simulation chain, proving its general good applicability in combination with MM5 optimized for this study.

Performing and analysing a regional climate change scenario in the upper Danube catchment The achievements summarized so far are the basis for goal number four, i.e. performing a long-time global climate change scenario for the 21st century according to the guidelines of the IPCC. This essentially allows to build a link from state of the art global climate modelling to the regional scale climate of the upper Danube catchment. The two-stage downscaling technique implemented and investigated within this thesis in principle is ready to handle any GCM-produced dataset. For GLOWA-Danube in particular a realisation of the more or less moderate A1B scenario was selected, simulated with ECHAM5, that got downscaled in the course of the present study applying the full combined dynamical-statistical downscaling apparatus, including the bias correction, as described above. The ECHAM5-A1B scenario results in an increase of global annual mean temperature of about 3.7 K at the end of the 21st century, compared to the 'present day' climate of the years 1961–1990. In the analyses of the downscaled highly resolved regional dataset, valid for the upper Danube catchment, the importance of the specific analysis method in view of the timescales and/or time periods relevant for the purpose of any particular climate change study or the specific interests of stakeholders has been pointed out. Thus, on the one hand the 110-year (1990–2100) linear trend of the climate change signal, relative to the mean of the years 1971–2000, has been evaluated, broken down in seasonal values. On the other hand the annual cycles of mean monthly values of two timeslices, one for present day conditions again for 1971–2000 and one for the period 2031–2060, have been juxtaposed for comparison. The future timeslice was chosen according to the requirements of GLOWA-Danube's stakeholders and their relevant planning horizons in fields such as hydroelectric power production or agriculture. The two 'key'-variables, particularly with regard to a (predominantly) hydrological project, precipitation and near surface temperature have been examined. To put the results of downscaled MM5 simulations in perspective also results from the regional model REMO, that were downscaled in an identical manner, were taken into consideration. Furthermore, the analyses of the linear trends were complemented with corresponding ECHAM5 raw data, that, however, at their coarse horizontal resolution of about 300 km, only comprise 5×5 grid boxes covering the upper Danube catchment. While being nested in the identical global meteorological environment and thus showing a more or less close correspondence under cursory inspection, both regional models follow the warming trend of the global model as well as the tendency towards less annual precipitation in the long run.

Both regional models, however, reveal some distinctly different features under a closer analysis, first of all for simulated precipitation but also for temperature. This reflects the complex interplay of processes, coupled with partially highly non-linear feedbacks, of the regional climate system. Here, in principle very different evolutions of the regional energy and mass balances, such as governed amongst others by cloud formation and radiation budgets, can result in distinctly different states of the regional climate, even due to seemingly marginal different formulations implemented within the regional models. Correspondingly, differences to the global simulation will not exclusively be due to the considerably different horizontal resolutions.

Specifically, all models agree on substantial warming in winter that reaches up to 6.7 K for the REMO simulation in the long time 110-years trend. This is particularly significant for an area with a substantial fraction of elevated mountainous terrain, that used to be covered by a layer of ice and snow in wintertime getting well replenished under present day conditions in the colder season. Concerning precipitation the models diverge noticeably, with a wintertime increase of about 8 % for $MM5_{vari\&bias}$ and a marginal decrease of around -1 % with $REMO_{vari\&bias}$. Irrespective of the trend of wintertime precipitation—the substantially warmer winter eventually would lead to vanishing glaciers in the area of the upper Danube catchment as has been diagnosed in cooperation with GLOWA-Danubes glaciologists (cf. GLOWA-Danube Global Change Atlas, Mauser et al. 2010). This in turn would alter the annual cycle of mean monthly discharge that's maximum in May under present day climate is predominantly governed by the melt of snow and ice starting in spring.

The most pronounced decrease of precipitation of about -30 % is to be expected, according to both regional simulations, for summer. This somehow would 'cut' the observed present day summerly rainfall maximum and thus could lead to critical shortages of water supply at least in some subregions of the upper Danube catchment at the end of the 21st century, a situation aggravated with temperatures about 5 K warmer than today. Also the total annual sums would decrease according to this regional expression of the A1B scenario, with deficits of roughly about -10 %.

The comparison of the two thirty year time slices, in contrast, shows an annual increase of precipitation sums, that is partially due to an substantial surplus of rain in spring that to some extent also is seen in the long-time trend. Furthermore, the moderate precipitation deficit analyzed in the linear trend for both regional scenarios in autumn is turned into a considerable positive contribution in the 'time-slice view'. The summerly decrease, on the other hand, here is only comparatively marginal.

All these considerations of mean values should not make one forget about the importance of simulated changes of patterns. The most striking findings here are the noticeable north-south gradients, i.e. essentially the height gradients for the temperature change, with relatively higher values for the elevated areas. This most probably is due to a different climate 'regime' in the future first of all in higher Alpine areas. Here a substantially decreasing portion of the energy budget will be consumed in the melting of snow, ice and glaciers, that partially will have retreated by then, leaving more energy to directly heat the near surface air. Last but not least, the high complexity of precipitation generation apparently results in complex patterns of the corresponding future change, that eventually might decide over subregions facing water shortage or even a surplus water supply.

The regional climate scenario generated within the present study and summarized above represents only one single possible future development of the key variables relevant for the use in the GLOWA-Danube project. Naturally, the future always is somewhat uncertain and only, if at all, a certain bandwidth of future conditions might be projected. Hence, a comprehensive set of scenarios has to be conducted to get some grasp of this bandwidth and to narrow it down as much as possible. This should help to give a reliable basis to devise flexible adaptation strategies to eventually master the actual challenges to come. In the framework of PRUDENCE (Christensen et. al 2007a) a subset of regional climate scenarios at a resolution of 50 km out of some combinations of four GCMs and ten RCMs was compiled, mainly for the A2 IPCC global scenario. Hagemann et al. (2009) performed regional simulations with REMO (50 km) driven by ECHAM5 for the B1, A1B and A2 scenarios for the 21st century. They focus on the large European catchments of the Baltic Sea, the Rhine and the Danube. The ENSEMBLES project (2009), amongst others, aims at a multi-model (global and regional) ensemble prediction system to systematically set up a probabilistic estimate of future regional climate change in Europe and West Africa under globale A1B conditions and to quantify corresponding uncertainties. Here, the RCM simulations are performed at 25 km horizontal resolution.

The regional scenario presented in this study complements these quite extensive studies on regional climate change. It is an unprecedented scenario for the whole 21st century covering a reasonably big European region, the upper Danube catchment, at a considerably high resolution of 1 km with a regional climate model involved. The approach of a two-stage dynamical-statistical downscaling method presented and evaluated here might well contribute to future studies to eventually reach the high resolution required by various impact models in a very cost-effective way.

The forth goal of this thesis thus was achieved successfully such as to exemplarily determine (based on the investigations and methods presented so far) the regional, highly resolved expression (in the upper Danube catchment) of a commonly used IPCC A1B global climate change scenario, that is seen as a highly realistic possible future development, and to provide analyses of the corresponding changes of the most important meteorological variables, i.e. precipitation and near surface temperature.

Interactive coupling of MM5 to the high resolution landsurface-vegetation-hydrology model PROMET

So far the meteorological simulations of this study were performed within their own closed modelling framework, i.e. the MM5 system. Naturally, in the interdisciplinary GLOWA-Danube project the meteorological simulation results had to prove their value first of all in the view of subsequent hydrological modelling. The MM5 itself, operated here in a one-way mode, had not to cope with any feedbacks of models from outside its very own model world. Thus MM5 could more or less guarantee, after appropriate optimizations performed for this study, for stable and realistic meteorological driving fields provided to the impact models. However, a quite promising opportunity might be missed to benefit from the expertise of other disciplines, participating in GLOWA-Danube and related to meteorological simulations, by operating MM5 in this self-contained way.

Goal number five of this thesis hence goes further, such as to open up MM5 to influences from other models that offer variables that are in principle relevant for the development of the regional meteorology. This is intended to allow for an overall consistent simulation approach, with each important process captured by the respective best-suited, specialized simulation model. In particular, the landsurface-vegetation-hydrology model PROMET, operated by the hydrology group of GLOWA-Danube, was favourably assessed as being capable of offering highly realistic simulations first of all of fluxes of latent and sensible heat, that are superior to corresponding values simulated with the original MM5 module, the so-called NOAH-LSM. PROMET allows for highly realistic simulations of upper Danube catchment discharge values (Mauser and Bach 2009), that are only possible, if the overall moisture budget, including evapotranspiration from the large variety of plants in the simulation area, is captured with a high degree of accuracy. This is achieved, on the one hand, by the implementation of sophisticated algorithms describing in detail the relevant processes of plant physiology according to the ambient (meteorological) conditions. The corresponding calculations, on the other hand, benefit on high resolution (1 km) data on landuse (including vegetation types) and soil properties, with detailed individual sets of parameters, available to PROMET.

In a one-way mode, the inalterably prescribed meteorology, as simulated with the 'stand alone' MM5, will nudge back the overall system to reality, even if some intrinsic tendencies for unrealistic drifts in subsequent models might exist. In a two-way coupled mode, however, a drift anywhere in an interactively coupled model even might further build up via the feedback over the atmosphere. To gain a certain basic understanding of the sensitivities to some key variables and parameters, relevant for the finally intended fully interactive coupling of MM5 and PROMET, at first some preparatory simulation experiments have been performed. This was done with pre-calculated (i.e. simulated beforehand with MM5's own 'NOAH' landsurface scheme) and systematically manipulated surface fluxes provided from an external input file as lower boundary conditions to the MM5. Here, it could be shown impressively, that the frequency of simulation data exchange, that was adequately set to 60 minutes in the one-way simulation mode, i.e. with atmospheric simulation data fed into PROMET without corresponding feedback to MM5, is definitely not sufficient and has to be set to at most 10 minutes in the two-way mode. Otherwise the overall system is clearly prone to drift away from a realistic development, as could be exemplified by a set of near surface meteorological variables. Furthermore, an experiment artificially changing the bowen ratio for every exchange time step while at the same time keeping the sum of latent and sensible heat flux fixed, clearly corroborated the necessity of an accurate simulation not only of the sum but of the relative proportion of both energy fluxes. Different bowen ratios lead to distinctly different developments of the boundary layer with effects that, for example, also point to differences in cloud formation.

The analysis of first experiments in a fully interactively coupled setup of MM5 and PROMET accordingly revealed some deficiencies in the simulation of the sensible heat flux by PROMET. The original version of PROMET concentrated on evapotranspiration, i.e. the latent heat flux, leaving the calculation of the sensible heat flux to a residuum of the surface energy balance. This understood, the hydrology group implemented an explicit calculation of the sensible heat flux as well. Concerning MM5, the formulation of the planetary boundary layer had to be exchanged, as the former module was not implemented in a way such as to clearly separate the atmosphere and the underlying lower boundary. Hence an unambiguous coupling to a different, external landsurface-vegetation model, such as PROMET, could not be performed consistently. Furthermore, for a well-defined determination of the turbulence regime, in addition to the energy fluxes also the lower boundary temperature calculated by PROMET had to be supplied to MM5.

These considerable modifications to both models and the coupling mechanism eventually allowed for highly realistic results in terms of precipitation and near surface temperature in the upper Danube catchment for a continuous simulation period of the four years of 1996–1999. Without the adaptations outlined above the pattern of accumulated precipitation was far beyond reality. After the redesign it compares well with the original, already quite realistic pattern simulated with MM5/NOAH (cf. Fig. 8.5) and sums up to a mean annual precipitation amount, that is closer to observations, with a positive bias of only about 5 % (compared 13 % for MM5/NOAH). Furthermore, the cold bias of 0.9 K in mean annual near surface temperature, obtained with the MM5/NOAH, is virtually eliminated in the MM5/PROMET simulations (bias 0.1 K), corresponding to altered surface heat fluxes with an increased sensible versus a reduced latent heat flux. Together with a noticeable improvement of temperatures, mainly in the summertime, this indicates a more realistic capture of processes in the (evapotranspirating) vegetation in PROMET.

The NOAH-LSM has been well adapted for the use with MM5 and over many years now proved its validity for comprehensive meteorological simulations in numerous studies as well as in the context of the present work (de Haan 2007, Miao 2007). Against this background it could not be expected a priori, that exchanging the NOAH-LSM would bring about any distinct, if at all, improvements. Upon overcoming some severe difficulties, encountered at the beginning, the results of the new model composite MM5–PROMET, however, prove highly promising. The noticeable improved simulations thus justify the substantial efforts made to eventually achieve the last goal of the present thesis, i.e. to create a new overall, fully coupled 'tool' for further regional climate studies, beyond the GLOWA-Danube project. This will allow for more detailed and comprehensive simulations of feedback effects between the atmosphere and the underlying surface with its highly resolved (inter-)active vegetation.

Thus, the present work also follows a request of Fowler et al. (2007). They complain that most climate change impact studies are designed in an offline (i.e. one-way) approach. One-way coupling to impact models was more or less the state of the art of modeling, on which the call of Leung et al. (2003) for 'coordinated end-to-end prediction systems to test the whole approach of impact assessment' was based on. Feedback effects, however, are undoubtedly important. Fowler at al. (2007) hence call for fully coupled 'whole system models' that are probably more appropriate for the investigation of regional climate change and for the development of corresponding adaptation and mitigation strategies. In the present dissertation a pragmatic approach has been devised, adapted and investigated to set up a fully two-way interactive model composite based on a RCM but additionally resorting to a statistical downscaling method to reach the horizontal resolution required by the hydrological model while keeping computational costs of the overall model down, thus improving its (technical) applicability.

Cooley et al. (2005) incorporated the effects of agricultural practice (i.e. first of all harvesting) into their coupled simulations of one summer season at a resolution of 10 km for the Southern Great Plains. They found significant differences in 2m-temperature, precipitation and soil moisture for early compared to late harvest scenarios. Feedback effects of climate change with altered regional conditions as well as agricultural decision-making and farm management in their view might exacerbate already hot and dry conditions. They suggest that realistic harvest scenarios should be an integral part of RCM studies. Such coupled simulation systems might help to identify proper mitigation strategies. With a cost-efficient 'whole system model' such as that created for GLOWA-Danube, with MM5–PROMET, simulation studies could be readily extended to climatological timescales at a considerably high resolution. MM5–PROMET allows for very detailed fine scale harvest patterns ($\sim$ 1km), that might be particularly relevant for highly fragmented arable regions, such as found in the upper Danube catchment and generally in Europe.

9.2 Outlook

Naturally, there are still open issues for further research. Some of which are more or less straightforward to address, and probably to solve, in some months worth of additional work. Other questions, going deeper into the complexities of the subject, call for endeavours that might appear on the respective agendas for some more years or decades.

Tying in with the last chapter of the present dissertation, it is most desirable to extend the simulations of the interactively coupled modelling system MM5/PROMET to substantially longer time periods for present day as well as future climate conditions. The performance of the overall system under present day climate has to be further investigated with simulations covering several decades. Moreover, the evaluation should be extended in view of hydrological results of PROMET, comparable to the investigations for the one-way mode (cf. chapter 6). This could be done right away in a follow-up project with a duration of several months. Particularly the ramifications of the bias correction, that would be necessary under ECHAM5 conditions, could be an issue to be investigated more closely in the context of the two-way coupling. Currently a follow-up project of GLOWA-Danube, concentrating on the whole state of Bavaria as research area, is in its planning phase (intended project duration 3 years). This project is aimed first of all at the investigation of sustainable, climate friendly use of land and natural resources, particularly with respect to the management of agriculture, forestry and ecosystems in the context of land consumption and urbanization, all under the conditions of a changing climate. This study will directly build on the achievements of the present work. Furthermore, within the interactive coupling of the RCM and the landsurface-hydrology model the vegetation will be set into a 'free running mode', allowing for plants to grow and spread as well as to die or even get extinct (regionally) according to altered environmental conditions. Direct interactions with a 'farming module' will be implemented, with processes such as harvesting and irrigation. Thus, it is intended to further develop a regional decision support system taking into account natural as well socioeconomic aspects.

In this study a coupled modeling system was developed and investigated, that was shown to simulate realistically climatological values of precipitation, 2m-temperature and general features of subsequent hydrological discharge in the upper Danube catchment. The timeshift in the annual cycle of mean monthly discharge values from June/July to May, however, found in the context of the one-way coupling of MM5 and PROMET, is somewhat dissatisfying. A study to identify the relevant shortcomings of the overall modelling approach could involve test simulations with a substantially higher resolution of PROMET (e.g. 100 m $\times$ 100 m). Ideally a considerably smaller river catchment, compared to the upper Danube area, but as well extending into higher Alpine regions and with corresponding high resolution datasets of landuse and soiltypes available, could serve as a test domain. This should allow to capture even better the whole variety of small scale surface patches and their diverse conditions, first of all in mountainous areas, where a realistically simulated fine scale distribution of snow, ice and surface temperatures is essential for the regional hydrology, particularly in times of thaw. The models in principle are ready for this kind of simulations that thus could be accomplished and evaluated within about one year.

The high-resolution meteorological simulation datasets (present day as well as future climate conditions) of the present study already have been provided to the 'Bayerisches Landesamt für Umwelt', that takes part in the project KLIWA (2010). Here, hydrological simulations for several comparatively small river catchments in Bavaria (e.g. the rivers Isar, Altmühl, etc.) are performed with the hydrological model WaSiM-ETH (Schulla and Jasper 2007). This cooperation ideally might be further intensified for investigations as outlined above.

Furthermore, additional (subgrid-scale) calculations or parameterizations of snow drift (cf. Bernhardt et al. 2010), the complex winterly moisture budget (Strasser 2008) and three dimensional radiation effects (Müller and Scherer 2005) might prove valuable, if not indispensable, for a correct simulation of the overall catchment discharge. All in all the time necessary for the implementation of new or improved algorithms and the various simulation experiments might well sum up to three years of work.

Another promising approach to tackle the timeshift in discharge simulations could be connected to the implementation of realistic diurnal cycles into the scaling functions of the statistical downscaling algorithm. So far the temporally more or less highly resolved RCM output data are refined with scaling functions defined on a daily basis only, due to the lack of sufficient high-resolution (in space and time) observational data on a climatological basis. In order to develop a more sophisticated approach under these circumstances, first of all the impact of explicit diurnal cycles, artificially specified on an individual basis for every variable to be downscaled, could be investigated in view of the downstream hydrological simulations. Assuming that a significant signal and some key-sensitivities can be detected in this way, in a further step realistic diurnal cycles, valid for the area of interest and depending e.g. on terrain height, have to be identified. This could be done, for example, by either collecting corresponding (to some extent already existing) data from field campaigns in appropriate areas, or by performing realistic high resolution regional simulations for a set of episodes typical for the research area. The COPS campaign, for example, investigates convective and orographically induced precipitation by observations as well as simulations (Wulfmeyer et al. 2008, 2011), however, only in low-mountain regions.

For a more precise and sophisticated fine-scale downscaling of precipitation, also idealized studies on small-scale precipitation variability in mountainous terrain, such as from Zängl et. al (2008), should be utilized. The sensitivity tests necessary could be performed within several month, whereas a more comprehensive study, including the collection and evaluation of observational data or high-resolution RCM simulations, might well extend such a study to two or three years.

A follow up project, that goes deep into the relevant parts of the model code of MM5, could, or rather should, tie in with the sensitivity experiments of chapter 4. Here, the systematic negative temperature bias in the afternoon hours together with the deficiencies of simulated near surface moisture offers a most intriguing starting point for further investigations. The intercomparison of an extended set of sensitivity simulations, including additional formulations of the planetary boundary layer, possibly could reveal substantial, more or less intricate (side) effects. The formation of explicitly resolved clouds, for example, interacts closely with the planetary boundary layer scheme and to some extent competes with the convection parameterization. First of all, entrainment and detrainment of clouds, implemented in the convective parameterization, might exert a considerable influence under certain circumstances on large scale clouds. The Grell scheme, for example, has no lateral mixing of a convective cloud with its environment and detrains all the properties of the cloud only at the cloud top into the ambient air. This possibly could well lead to saturation in the respective grid box and thus the formation of an explicitly resolved cloud, i.e. a cloud covering the entire box at the vertical level determined by the cloud top of the convective cloud. Therefore, the short as well as long wave radiation would be directly affected and thus also the surface energy budget. Particularly in the afternoon, when the convective parameterization is active, this would lead to reduced incoming solar radiation and hence to lower near surface temperatures as simulated with MM5. The findings of Hohenegger et al. (2008) support this assumption. They performed RCM simulations at a resolution of 25 km and additionally at cloud-resolving scale of 2 km. The cloud-resolving simulations allowed for reduced near surface cold and moist biases together with an improved radiation budget compared to the coarse scale simulations, that have to resort to a convective parameterization scheme. Given a functional chain as straightforward as outlined above, leading to the cold bias, a corresponding study could be accomplished within a few months. In this case, only comparatively short periods, such as a hand full of summer seasons, would have to be simulated, and the relevant processes could be diagnosed with the help of the standard output data of MM5.

Further investigations on this issue should build on related studies. Zhang and Zheng (2004), for example, performed a set of experiments over the central United States for a 3 day long summertime episode (with weak gradient-flow, little organized convection and little topographical forcing) using MM5 with five different PBL schemes (and the Kain-Fritsch convective parameterization). They found a considerable sensitivity of simulated near surface wind as well as temperature. Here, the Eta-PBL simulated a realistic diurnal cycle of temperature but revealed a considerable cold bias. Fernández et al. (2007) also find a cold bias of 5 K in their study with 16 5-year long MM5 simulations, each testing two different options of explicit moisture, cumulus convection, PBL and radiation scheme, respectively. They suspect, without further investigations, excessive moisture availability in the soil module as being responsible for this persistent deficit. Excessive soil moisture and thus surplus evapotranspiration also might explain the moist bias in the lower atmosphere found in the reference run of chapter 4. Similar (seasonal or climatological) simulations with the basic setup used in the present study could give valuable insights concerning the respective cold and moist bias found here. Zhang and Zheng (2004) as well as Fernández et al. (2007) did not use z-diffusion. Whereas the simulations of Zhang and Zheng for the Great Plains probably are not affected significantly by the side effects of the terrain following σ-diffusion, this will be quite different for simulations over mountainous parts of the Iberian Peninsula, performed for the latter study. Thus, based on the findings of this disseration, corresponding sensitivity tests on this issue in the upper Danube catchment or any other mountainous area should definitely resort to truly horizontal numerical diffusion.

A further, probably much more complex issue to investigate, could be connected to the Monin-Obukhov similarity theory (Stull 1988, Garratt 1994, Jacobson 2005), governing the calculation of surface layer fluxes of momentum as well as sensible and latent heat. The corresponding formulations are basically identical in various meteorological models, thus inaccuracies here could explain that a negative temperature bias combined with too much near surface moisture in the afternoon hours is found in a similar manner for different meteorological models (see above). Probably the key parameters of this theory actually are not really that 'fundamental' as assumed for quite a long time. The basic concepts of the Monin-Obukhov theory are more and more challenged, and hence improved, by comprehensive field experiments such as MAP, the Mesoscale Alpine Program (Rotach and Zardi 2007), or studies such as performed by Laubach and McNaughton (2009). The Monin-Obukhov theory, moreover, is a topic of ongoing, quite fundamental, if not vigorous, discussions (Andreas 2002, van de Wiel et al. 2011a, 2011b). Tackling this issue thus obviously still calls for more major endeavours presumably for several years. Beyond more basic numerical simulation experiments also new field experiments could be involved, particularly over very complex terrain (such as Martins et al. 2009), as well as lab experiments using water tanks and wind-tunnels (Loureiro et al. 2008, Hattori et al. 2010).

The overall meteorological regional modelling system, i.e. the optimized MM5 together with the statistical downscaling algorithm, as devised, refined, and analyzed in the present dissertation, is designed in way such as to easily switch to input datasets corresponding to other global climate change scenarios, simulated by ECHAM5, as well as to datasets from other global climate models. Thus, in order to open up a certain bandwidth of possible future climate developments in the upper Danube catchment, it suggests itself to perform analogous regional climate change studies for the 21st century, such as presented in chapter 7 for an A1B scenario, for other main members of the scenario–family conceived by the IPCC. Corresponding global ECHAM5 simulations have also been conducted and already considered in the IPCC's fourth assessment report for the A2 and B1 scenario (cf. figures 2.4 and 2.5), each of which in three slightly differing realisations. These datasets are readily available and could be fed into the downscaling mechanism of the reel with no need for any additional adaptations of the model chain.

Furthermore, several other AOGCMs have been operated based on the IPCC scenarios to generate corresponding data sets, that, whilst agreeing in their general trends of future global climate, reveal some differences to each other, thus reflecting to some extent the inevitable uncertainties concerning the future development. The datasets of other models than ECHAM5 in principle are as well appropriate as input to MM5 with presumably only minor changes of the data preprocessing of the MM5 system.

All in all this aims at virtually building a multi-member ensemble of climate change scenarios to be projected onto the region of interest by the two-stage downscaling technique of the present study. The time necessary to compile the high-resolution regional scenarios depends first of all on the availability of corresponding AOGCM output data and the available computational resources. Under favourable circumstances a reasonable comprehensive ensemble should be accomplished within about one year.

Another obvious direction of future research on regional climate change, based on the present work, would be to transfer the downscaling and moreover the ensemble approach outlined above to other regions of interest, i.e. preferably other river catchment areas, maybe even those covered already by the GLOWA research initiative. A possible obstacle to this might be the lack of long time, high resolution observation data necessary for the 'training' of the statistical part of the downscaling. Furthermore, observational data on climatological time scales are also necessary for the validation of regional climate modelling for present day climate conditions. In major regions of Africa (cf. projects GLOWA-Volta and GLOWA-Impetus, focussing on rivers Volta, Drâa, and Ouémé, in North and West Africa) for instance, this will be a severe issue. A fair estimate on the time to spend for such studies hence does not only depend on computational resources but on the efforts necessary to obtain and to process the required observations. This might easily add up to some more months to be allocated for corresponding studies, naturally only if data are available at all. Given a certain reliability of the re-analysis driven RCM simulations in the region of interest, these data might be taken as a reasonable proxy for observations at the resolution of the RCM. Thus, as a working solution, they could be used at least as the 'observational' basis of a coarse scale bias correction.

All these comprehensive simulations suggested above could contribute substantially to (or even go beyond) other impressively extensive overarching projects on future regional climate, such as PRUDENCE and ENSEMBLES (see above), however, at a considerably higher horizontal resolution of 1 km. In view of subsequent climate impact, particularly in hydrology, future work as outlined above, building on the present study, could readily complement the work of Hagemann et al. (2009), who performed regional climate scenarios with REMO (50 km) driven by ECHAM5 simulations of the B1, A1B and A2 scenarios. The approach presented in this dissertation could be easily extended onto one of their research areas, e.g. the Rhine catchment. Furthermore, Graham et. al (2007b) use a subset of GCM-RCM simulations (resolution 50 km), performed in the framework of PRUDENCE, to drive two different hydrological models for climate change studies for different European drainage basins. In a case study for the Lule river basin in Sweden (Graham 2007a), for example, they fortunately also find a convenient impact of climate change, i.e. a considerable increase (in their ensemble mean) of future hydropower potential. Corresponding studies, related to specific stakeholders, could as well benefit from the achievements of this work.

The high quality of the RCM simulations under reanalysis input and the proven validity of bias-corrected GCM-RCM simulations, particularly in view of subsequent hydrology, should help to generally reduce uncertainties of regional climate studies, first of all in mountainous terrain. Some of the concepts, ideas and findings of the present work could well be transferred to other RCMs. First of all the successor of the MM5-system, i.e. the WRF (weather research and forecasting) model (Skamarock et al. 2008) is an obvious candidate for such a venture. The WRF meanwhile is a stable and versatile new model, that offers similar options of physics schemes and parameterizations as MM5 and as well naturally allows for regional climate simulations. Given a good performance of the interactively coupled approach between MM5 (or another RCM, such as WRF) and the high resolution landsurface-hydrology model PROMET also for climatological simulation runs driven by GCM data, as suggested above, corresponding studies based on the achievements of the present dissertation could reach a whole new depth and quality. The work of the present dissertation thus all in all could also make a considerable contribution to future studies in the sense of an end-to-end (interactive) multi-model (GCMs, RCMs, hydrological models), multi-scenario (B1, A1B, A2, etc.), multi-area ensemble, that ideally would also be taken into consideration by the IPCC.

Last but not least there remains one paramount issue fundamental to all climate research, that, however, fairly leaves the scope of the present dissertation and any more or less closely related follow-up studies: (even further!) improved global climate models and simulations. In chapter 5 it could be shown, that unfortunately even comparatively small inaccuracies in the simulated large scale flow can induce substantial deficiences in subsequent regional modelling. Tremendous progress has been made in the field of global atmosphere–ocean general circulation models over the last decades. Hence, confidence is well justified, that the next few years and decades will bring about global models with an unseen degree of accuracy, with more and more processes being better understood and captured in the simulations. At the same time, the horizontal resolution of AOGCMs will be increased dramatically, such as if to leave regional models expendable. However, there will still be demand for even higher resolutions, particularly in complex terrain, that cannot be met by global models for quite a long while. The ongoing progress in computer technology not only will allow for higher resolutions of global models but of regional models as well, eventually allowing for regional climate simulations with grid sizes in the range of some few kilometers or below—thus, by the way, making any additional statistical downscaling unnecessary.

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