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Special Issue: Workshop on Regional Climate Modeling

Guest Editors: **Tomas Halenka and Daniela Jacob**
Local Organizer: **András Horányi**

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Preface

Climate models in general and regional climate models (RCM) in particular are essential tools for the exploration of the future change of the global and regional climate. Their role is continuously increasing all over the world and inevitably in Europe. In the recent past several international projects (most of them supported by the European Commission) were initiated with the main objectives to provide quantitative estimates for the expected climate change in Europe. It is now more and more recognized that the impact of the climate change can only be investigated based on the results of climate models. In the last few years more and more activities in this field were also carried out in Central and Eastern Europe (CEE). Another important boost was given to these developments: the successful application and acceptance of the CECILIA (www.cecilia-eu.org) and CLAVIER (www.clavier-eu.org) projects in the 6th Framework Programme of the European Commission. These collaborations are not "only" dealing with the quantification of the regional climate change (together with the related uncertainties) based on regional climate models, but also studying the impact of the foreseen change on agriculture, tourism, air pollution, etc.

The first important event in the field of regional climate modeling in Central and Eastern Europe took place in Prague, at the end of 2004, when Charles University organized a regional climate modeling gathering ("Workshop on Regional Climate Modeling and Mini-Symposium on Climate Change in Europe"). This meeting can be considered as an important milestone for building those teams, which were later assembled under the umbrella of the CECILIA and CLAVIER projects. Later on in the course of the above-mentioned two projects, the CLAVIER project initiated another workshop on regional climate modeling with the primary aim to discuss key scientific issues on regional climate modeling (model development, validation, and application) and, furthermore, to strengthen the cooperation between the CECILIA and CLAVIER projects. This latter event was held at the headquarters of the Hungarian Meteorological Service in Budapest at February 4–6, 2008. It was attended by approximately 50 scientists from 11 countries (mostly from the CECILIA and CLAVIER partners). The presentations of the workshop were put to the homepage of the Hungarian Meteorological Service (http://www.met.hu/seminars/rcm2008.php) after the meeting. Moreover, it was decided that a Special Issue of the Quarterly Journal of the Hungarian Meteorological Service (IDŐJÁRÁS) would be compiled from the peer reviewed scientific papers of the workshop. It is our great pleasure to present this Special Issue of IDŐJÁRÁS not only for those, who are working in the field of regional climate *modeling, but also for those, who are dealing with the impact assessment of climate change over the Central and Eastern European territory. We are convinced that the further research and development activities in the field of regional climate modeling are essential for the reliable estimates of the climate change over Central and Eastern Europe, and we hope that this Special Issue can be a modest contribution to this challenge with its 9 scientific articles (and two introductory project descriptions) in this volume. It is furthermore anticipated that this issue will also help to promote the further cooperation between the CECILIA and CLAVIER EU projects.*

We are extremely grateful to all the authors, who contributed to this edition of IDŐJÁRÁS and also for the dedicated reviewers significantly helping to improve the scientific content of this thematic Special Issue.

László Bozó
Editor-in-Chief

András Horányi
Local Organizer of the RCM workshop

Editorial

Regional climate modeling activities in CECILIA project

Introduction

Although the broad response of global climate to increased greenhouse gas concentrations is well established, many unknowns remain in the regional details of projections of future climate change. The floods and droughts, which occurred in recent summers in the Central and Eastern European (CEE) region, highlight the importance of the hydrologic cycle and water management in Elbe and Danube river catchments in response to the occurrence of precipitation extremes. In summer of 2002, the Czech Republic experienced some of its worst floods in history with the Vltava river inundating Prague causing severe and widespread damage. The 2003 heat wave, one of the severest heat waves on record in Central and Western Europe causing both human losses (Kysely, 2004) and extensive damage to human activities and natural ecosystems, demonstrated the importance of the health impacts of extreme conditions that could also lead to considerable changes in air quality, both regionally and in major urban centers. The possibility of changes in the frequency and intensity of these extreme events is one of the most dreaded manifestations of anthropogenic climate change. A number of studies have linked the occurrence of the extreme events to anthropogenic forcings (Beniston and Stephenson, 2004; Schär et al., 2004; Pal et al., 2004; Meehl et al., 2004; Meehl and Tebaldi, 2004). Impacts on agriculture and forestry affecting the economy of countries in the region are extensively studied as well (Menzel et al., 2006; Menzel et al., 2003; Hafner, 2003; Gobron et al., 2005).

While coupled atmosphere-ocean general circulation models (AOGCMs) provide basic information on the development of the climate change, their horizontal resolution is still too coarse to describe in detail processes affecting extreme events at the regional scale (Gates et al., 1996). In order to regionally enhance the AOGCM information, a number of regionalization techniques have been developed (Giorgi et al., 2001). One of them is the use of limited area regional climate models (RCMs) nested in driving fields from reanalysis or GCMs similarly as previously done in numerical weather prediction for decades (Giorgi and Mearns, 1999). The main advantage of this method is that it can reach with the same or even less computational resources horizontal grid intervals of a few tens of km, and thus, RCMs can provide improved simulation of extreme events (e.g., Huntingford et al., 2003; Frei et al., 2003). During the last decade, RCMs have been increasingly used to examine climate variations at scales that are not resolved by global models. To the extent that they produce realistic climate simulations, such models can be powerful tools in the study of regional climate impacts.

Thus, the aim of the EC FP6 project CECILIA (Central and Eastern Europe Climate Change Impact and Vulnerability Assessment) is to go into these regional details assessing the impact of climate change at the regional to local scale for Central and Eastern Europe using very high resolution simulations in order to capture the effects of the complex terrain of the region. In this region the need for very high resolution studies is particularly important. The region is characterized by the northern flanks of the Alps, the long arc of the Carpathians, and smaller mountain chains and highlands in the Czech Republic, Slovakia, Romania, and Bulgaria that significantly affect the local climate conditions. A resolution sufficient to capture the effects of such topographical and associated land-use features is necessary. Therefore, the central internal *objectives of CECILIA are to improve regional climate scenarios and their localization for climate impacts models, and comparing these results against the results of previous and ongoing projects to assess the added value of dynamical downscaling at very fine scales. The proposed research will benefit greatly from the results of previous and ongoing EC projects, like:*

- *"Modeling the Impact of Climate Extremes (MICE)";*
- *"Statistical and Regional Dynamical Downscaling of Extremes for European regions (STARDEX)";*
- *"Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects" (PRUDENCE);*
- *"ENSEMBLE-based Predictions of Climate Changes and their Impacts" (ENSEMBLES).*

The goals will be achieved mainly using very high resolution RCMs run locally for individual targeted areas. As for climate change scenario projections, the production of two time slices are realised covering years 2020–2050 and 2070–2100, with 1961–1990 as a reference period. Weather pattern changes as well as changes of extreme events appearance are addressed within the project as they affect the important sectors of the economies and welfare of individual countries in the CEE region. To address the uncertainties, the results of previous or ongoing projects (PRUDENCE, ENSEMBLES) will be evaluated and used in CECILIA. The selected applications of the outputs are supposed toward water resources and management, agriculture, forestry, air quality and health. The objectives will be achieved through the following specific tasks:

- *To collect, assess, and make available for first local impact studies the scenarios and climate simulations produced in previous relevant projects, especially PRUDENCE, STARTDEX, MICE, and ENSEMBLES, where available (WP1, see Giorgi and Coppola, 2007);*
- *To adapt and develop very high resolution RCMs for the region (10 km grid spacing) and perform regional time-slice nested runs driven by ERA-40 data (Uppala et al., 2004) and by GCMs for selected GHG change scenarios (WP2);*
- *To verify the model results, compare RCM and statistical downscaling results, analyze and develop the methods for verification, particularly at local scales, to provide the scenarios (WP3);*
- *To estimate the effect of global climate change on extreme events in the region, including the assessment of the added value of high-resolution for the simulation of the relevant processes and feedbacks. To evaluate uncertainties in regional projections by comparing results from previous projects (WP4);*
- *To assess (using high resolution downscaling results) the impacts of climate change on the hydrological cycle and water resources over selected catchments; the effects of climate change on the Black Sea (WP5);*
- *To study (based on the high resolution downscaling results) the impacts of climate change on agriculture and forestry, carbon cycle and selected species (WP6);*
- *To study (based on the high resolution downscaling results) the impacts of climate change on health and air quality (photochemistry of air pollution, aerosols) (WP7).*

The main goal of the CECILIA project is to integrate results from different previous and ongoing modeling activities and approaches to provide the basis for very high resolution climate *change impact and vulnerability assessment in important human activity sectors and natural ecosystems. It is prohibitive to cover within the STREP (Specific Targeted Research Project) all the sectors in their complexity, so that our analysis is limited on some key areas of specific interest to the CEE regions. Nevertheless, the scope of the project is big enough and highly multidisciplinary, which required quite big team. The consortium comprises 16 partner institutions (see Table 1) that bring together a wide range of inter-disciplinary expertise and experience in the areas of climate change modeling, statistical analysis, climate change impact assessment, as well as anthropogenic and biogenic pollutant emissions. Reflecting the shared and overlapping expertise and interests of the partners, most of the work packages involve contributions from several partners, under the direction of a lead partner. As the targeted area is Central and Eastern Europe the substantial part of participant institutes comes from this area (10–12, depending on the political or geographical point of view), complemented by selected partners from western part of EU to add necessary access to experience, know-how, and data for working on the project.*

Table 1. List of partners in project CECILIA

Partner name	Partner short name	Country
Charles University, Prague	CUNI	Czech Rep.
The Abdus Salam ICTP, Trieste	ICTP	Italy
Météo-France, Toulouse	CNRM	France
Danish Meteorological Institute, Copenhagen	DMI	Denmark
Aristotle University of Thessaloniki	AUTH	Greece
Czech Hydrometeorological Institute, Prague	CHMI	Czech Rep.
Institute of Atmospheric Physics, Prague	IAP	Czech Rep.
Swiss Federal Institute of Technology Zurich	ETH	Switzerland
University of Natural Resources and Applied Life Sciences, Vienna	BOKU	Austria
National Meteorological Administration, Bucharest	NMA	Romania
National Institute of Meteorology and Hydrology, Sofia	NIMH	Bulgaria
National Institute of Hydrology and Water Management, Bucharest	NIHWM	Romania
Hungarian Meteorological Service, Budapest	OMSZ	Hungary
Forest Research Institute, Zvolen	FRI	Slovakia
Warsaw University of Technology, Warsaw	WUT	Poland
Eötvös Loránd University, Budapest	ELU	Hungary

CECILIA RCMs and simulation strategy

One of the commonly used RCMs in the targeted region is the model RegCM distributed freely from ICTP. The model was originally developed by Giorgi et al. (1993a,b) and later augmented as described by Giorgi and Mearns (1999), Pal et al. (2000), and Pal et al. (2007). The dynamical core of the RegCM is equivalent to the hydrostatic version of the NCAR/Pennsylvania State University mesoscale model MM5. Surface processes are represented via the Biosphere-Atmosphere Transfer Scheme (BATS – Dickinson et al., 1993) and boundary layer physics is formulated following a non-local vertical diffusion scheme (Giorgi et al., 1993a). Resolvable scale precipitation is represented *via the scheme of Pal et al. (2000), which includes a prognostic equation for cloud water and allows for fractional grid box cloudiness, accretion, and re-evaporation of falling precipitation. Convective precipitation is represented using a mass flux convective scheme (Giorgi et al., 1993b), while radiative transfer is computed using the radiation package of the NCAR Community Climate Model, version CCM3 (Giorgi et al., 1999). This scheme describes the effect of different greenhouse gases, cloud water, cloud ice, and atmospheric aerosols. Cloud radiation is calculated in terms of cloud fractional cover and cloud water content, and the fraction of cloud ice is diagnosed by the scheme as a function of temperature. For more details on the use of the model see Elguindi et al. (2006). The model has been already applied in targeted regions, e.g., by Halenka et al. (2006) and Busuioc et al. (2006).*

Another RCM has been used recently, starting from an operational NWP model used in several national meteorological services in the targeted domain. This is the ALADIN-Climate model, and first experiences from its development can be found in Huth et al. (2003). Originally, the limited-area prediction model ALADIN has been developed by the international team headed by Météo-France, and modification for RCM purposes started in 2001 in cooperation with CHMI in Prague. ALADIN is a fully three-dimensional baroclinic system of primitive equations using a two-time-level semi-Lagrangian semi-implicit numerical integration scheme and digital filter initialization. For the description of the model and its parameterizations, refer, e.g., to Bubnová et al. (1994) and Váňa (1998). The physical parameterizations package comprises gravity wave drag parameterization, implicit horizontal diffusion computed in spectral space (fourth order and increasing with height), vertical diffusion and planetary boundary layer parameterization, constant analyzed sea surface temperature and amount of sea-ice, an improved version of the ISBA (Interaction Soil Biosphere Atmosphere) scheme, including an explicit parameterization of soil freezing (prognostic variables in ISBA: surface temperature, mean soil temperature, interception water content, superficial soil water content, total liquid soil water content, total frozen soil water content), simple parameterization of snow cover, soil characteristics (texture, depth) that are point-dependent, vegetation characteristics that are point- and month-dependent, simplified radiation scheme called at every time step, mass flux convection scheme including the entrainment profile, specific humidity as a solely prognostic variable: no storage of condensate; evaporation of falling rain; treatment of the ice-phase, and a sophisticated diagnostic cloud (and cloud content) method used for radiative transfer calculations. For running the ALADIN model in a climate mode, a few modifications had to be made, which include mainly changes in lower boundary condition specifications and availability of restart.

Another way to increase resolution is to use GCM with a variable horizontal resolution, e.g., model ARPEGE (Déqué and Piedelievre, 1995; Déqué et al., 1998), an approach that, however, requires even larger computational resources than RCMs. Basically, there is close connection in modeling activities of the CECILIA project to the project ENSEMBLES, where all the three models mentioned above are used as well, both for climate change projections and model inter-comparison and validation. Since the field of regional climate prediction is still evolving, the skill of RCMs in simulating climate variability has not been extensively evaluated. This is planned within the framework of the project ENSEMBLES for simulations at 50 and 25 km resolution driven by ERA-40 reanalyses. As part of the ENSEMBLES project, transient scenario runs of one hundred year length (1950–2050, some even longer) are also planned under different greenhouse gases (GHG) and aerosol forcings. In CECILIA, a detailed analysis and use of the results of the project ENSEMBLES is planned for focused initial impact studies in our target region (WP1 and starting stage of WP4,5,6,7). However, next to this initial phase, the main objective of this proposal is to adapt the RCMs used for ENSEMBLES (ALADIN-Climate and RegCM) for very high resolution *(grid spacing of 10 km) simulations over selected sub-domains, which will provide additional information related to the complex terrain of the region. The assessment of the role of significant but previously not resolved topographical features and land use patterns will be provided in these experiments as well as the evaluation of the sensitivity of the simulations to the choice and size of the model domain. Furthermore, for the CECILIA project, last 50 years of present century was run by the ARPEGE (CNRM) and RegCM@25km (ICTP) to provide driving fields for ALADIN-Climate and RegCM families partners, respectively, in end-of-century time slice.*

In addition, there is statistical downscaling involved in the project (Busuioc et al., 2006; Huth, 2002, 2005) both for comparison and localization of the model results. The availability of different methodologies giving often different results implies that a full assessment of the uncertainties in regional climate change simulation may require the use of multiple techniques (as proposed in this project). The CECILIA project is also going to provide insights on the validation and relative merits of statistical and dynamical downscaling, in particular as applied to provide local climate information.

The higher resolution enables not only more detailed description of the topography and land use, but it allows to introduce new processes, as interactive interaction of climate change and air quality, subgrid effects, etc. The preliminary results show the promising benefits of very high resolution towards the use in impact studies. More detailed analysis of results, which is clearly beyond the purpose of this introduction, is either already done or it is planned in the near future within the project. Moreover, development of new features in the parameterization of high resolution physics in the models is expected. Adjustment of large scale precipitation parameterization has been mentioned already as improving the precipitation results significantly in very high resolution. Exploration of the possible improvements of high resolution regional climate modeling by testing new parameterization schemes better adapted to this resolution is another objective of modeling activities within the project.

Previous results show the possibility of the changes of statistical distribution of climate parameters in our targeted domain. Despite the relative agreement of climate-change scenarios concerning the changes in extremes over this region, a significant uncertainty remains with regard to their exact magnitude and the attribution of the causes for these changes. Some studies have highlighted the role of large-scale circulation changes, but land-atmosphere interactions are clearly of key relevance as well. Moreover, certain aspects central to this issue are often not well represented in GCMs (land surface heterogeneity, complex topography, convection), or even in RCMs. Very high-resolution simulations could help investigating some of these open questions and yield more accurate estimates of future changes in extreme weather events over the targeted regions.

The basic objective of modeling activities in CECILIA project is to produce simulations on targeted domains for a past period (1961–1990) driven by ERA-40 reanalysis used for validation of the models, as well as for a reference period (1961–1990) and scenario time slices (2021–2050 and 2071–2100) based on ENSEMBLES 6FP EC IP A1B GCM simulations. Two models have been supposed to be used as source of driving fields over six target areas, ALADIN-Climate family using stretched climate change transient run by ARPEGE-Climate for ENSEMBLES project, RegCM family using RegCM transient ENSEMBLES run for whole Europe in 25 km resolution driven by transient run of ECHAM5. While the stretched ARPEGE run provides reasonable resolution in targeted regions for direct application of 10 km resolution RCM, the difference between 10 km resolution of RegCM and the resolution of other common global models is too large, that is why the double-nesting using 25 km RegCM run as an intermediate step is necessary. Some of the results already achieved are discussed in papers within this Special Issue of IDŐJÁRÁS.

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Tomas Halenka

Guest Editor on behalf of the CECILIA project

Short overview of the CLAVIER project

Herewith I would like to give a short overview of the CLAVIER project. The project is founded by the European Commission's 6th Framework Programme as a Specific Targeted Research Project under the thematic sub-priority "Global Change and Ecosystems". CLAVIER has a duration of three years (until the end of August, 2009) with the coordination of the Max Planck Institute of Meteorology.

The overall aim of CLAVIER is to provide contribution in order to successfully cope with ongoing challenges in Central and Eastern Europe (CEE) through the economic and political transition, continuing vulnerability to environmental hazards and longer term impacts of global climate changes. We focus on three CEE countries – Hungary, Romania, and Bulgaria and address the following scientific goals:

- *Investigation of ongoing and future climate changes and their associated uncertainties in Central and Eastern European Countries (CEEC);*
- *Analyses of possible impact of climate changes in CEEC on weather pattern and extremes, air pollution, human health, natural ecosystems, forestry, agriculture, and infrastructure as well as water resources;*
- *Evaluation of the economic impacts of climate changes on CEEC economies, concentrating on four economic sectors, which are agriculture, tourism, energy supply, and the public sector.*

We wish to achieve our goals through investigation of the links between climate change and its impact on weather pattern and air pollution, extreme events, water resources, as well as on natural ecosystems, infrastructure, and human health. As a result, the impact of climate changes on economics of the countries mentioned above is evaluated.

The first step is to provide reliable climate evaluation scenarios of the first half of the 21st century for impact researches from CEE. Three different regional models are used in the project to form a small ensemble. An article related to regional modeling activity of the CLAVIER project is presented later in this issue.

A crucial part of the project is the establishment of an effective interface between the climate modeling and climate impact assessment communities. This interface is realized by dynamical and statistical techniques. Dynamic modeling and adaptation at very fine scales (3 to 1 km grid spacing) provide an input for the case studies in the field of hydrology and agriculture, and the multi-scale simulations are used to investigate model resolution suited for representation of meteorological and climate extreme events. Statistical downscaling techniques are applied for directly derived parameters of weather and climate extremes as well as climate impact parameters in the fields of ecosystems, health, infrastructure, and economics.

Analyses of possible impact of climate changes in CEE on weather pattern and extremes, air pollution, human health, natural ecosystems, forestry, agriculture, infrastructure, and water resources stretches through several work packages.

Within CLAVIER we not only analyze weather regimes for the region of CEE, but study their future changes and implication to air pollution levels. While the methodology of the work on characterization of the current regional climate is based on a synoptic-climatological approach, classification methods are applied to complete statistics of weather regimes for climate scenarios. As a result, composite meteorological datasets are calculated and will be used in a regional scale air pollution model.

It is generally expected within the climate research community that the extreme events will increase under climate change conditions, they will occur more often and will become more intense. Here we analyze past and future trends of extreme events in CEE based on existing regional climate model simulations. Special emphasis is put on the summer drying problem, which is a systematic bias in the simulation of today's mean climate and is typical for many regional models. We also focus on the potential impacts of extreme events on forestry and water management as well as soil and agriculture.

One of the main aims of the project is the production of future hydrological and agricultural scenarios. This includes the investigation of changes in the hydrological regime of various catchments, the estimation of changes in riverine flood characteristics, as well as the estimation of the long-term evaporation rates from large lakes. An analysis of changes in water stress for crops and changes in low water conditions is taken into account.

Various methods are developed and integrated within the project to reveal the spatial-dependent interrelationship between the climate/weather parameters and the impact processes. Here we consider the following impact case studies: grassland, roads, heat waves, buildings (roof), and ragweed.

The knowledge gained through the scientific goals mentioned above builds the basis for evaluation of the economic impacts of climate change on national economies. Four sectors are of particular interest – agriculture, tourism, energy supply, and the public sector. Furthermore, ten case studies for selected regions in Hungary, Bulgaria, and Romania are identified. As a result, the overall macroeconomic relevance of the studied phenomena is drawn.

A substantial part of the project is in close contacts with a wide range of user groups from CEE countries, who will benefit from our results. CLAVIER closely cooperates with the EU projects ENSEMBLES and CECILIA.

Please visit the project web-site to learn more about CLAVIER: www.clavier-eu.org.

Daniela Jacob
Guest Editor on behalf of the CLAVIER project

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Regional climate modeling activities in relation to the CLAVIER project

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Abstract—Observational records show that the global climate is changing and these changes are visible in the Central and Eastern European Countries (CEEC). Certainly negative impacts of climate change will involve significant economic losses in several regions of Europe, while others may bring health or welfare problems somewhere else. Within the EU funded project CLAVIER (Climate ChAnge and Variability: Impact on Central and Eastern EuRope) three representative CEEC are studied in detail: Hungary, Romania, and Bulgaria. Researchers from 6 countries and different disciplines identify linkages between climate change and its impact on weather patterns with consequences on air pollution, extreme events, and water resources. Furthermore, an evaluation of the economic impact on agriculture, tourism, energy supply, and public sector will be conducted. CLAVIER focuses on ongoing and future climate changes in CEEC using measurements and existing regional scenarios to determine possible developments of the climate and to address related uncertainties. Three regional climate models are used to simulate the climate evolution in CEEC for the period 1951 to 2050, the future regional climate projection being the first half of the 21st century. The issue of climate change uncertainties is addressed through the multi-model and multi-scenario ensemble approach. As a result, CLAVIER establishes a large data base, tools, and methodologies, which contribute to reasonable planning for a successful development of society and economy in CEEC under climate change conditions. Current regional climate projections show a strong warming and drying during the summer months, which seems partly due to a systematic error in model simulations. Detailed validation of the CLAVIER simulations, which goes much beyond this paper, is needed, and the results have to be related to possible climate changes projected for the region in future simulations.

Key-words: climate, climate change signal, regional climate change, regional climate modeling, validation, Central and Eastern Europe, temperature, precipitation

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1. Introduction

The nations in Central and Eastern Europe (CEE) face triple challenges of the ongoing economic and political transition, continuing vulnerability to environmental hazards, and longer term impacts of global climate change. Domestic development of market economies and democratic institutions is taking place in the context of complying the rules of these international bodies. At the same time, vulnerability to natural and human environmental hazards knows no boundaries in time and space. Examples include a series of extreme floods hitting the Tisza basin in the period of 1998–2001, the catastrophic dam failure such as the Baia Mare gold mine dam failure in Romania which resulted in cyanide pollution of the Lapus-Somes-Tisza-Danube rivers (January 2000; Relief Web, 2000), a number of other flood events such as the Labe/Elbe and Danube rivers (August 2002), a sequence of mostly flash flood disasters throughout Romania in 2005, plus the ongoing menace of air pollution, drought, deforestation, land slides, and soil erosion. In addition to these challenges, long term global climate change may offer opportunities as well as threats to environment, resources, and national well-being amidst the on-going stresses of transition and capricious environmental forces (most of it citation from Climate change in Central and Eastern Europe: Introduction, GeoJournal 57, 2002, 113–115).

It is urgently needed to address the ongoing and future climatic changes and possible consequences in CEEC.

Therefore, CLAVIER addresses the following three scientific goals:

1. Investigation of ongoing and future climate changes and their associated uncertainties in CEEC.
2. Analyses of possible impact of climate changes in CEEC on weather pattern and extremes, air pollution, human health, natural ecosystems, forestry, agriculture and infrastructure as well as water resources.
3. Evaluation of the economic impacts of climate changes on CEEC economies, concentrating on four economic sectors, which are the agriculture, tourism, energy supply, and public sector.

Objective 1 is to provide reliable climate evolution scenarios of the first half period of the 21st century for impacts research in the CEEC region. The issue of climate change uncertainties is particularly addressed. This objective will be achieved through assembling and assessment of existing climate scenarios for the region, the validation and improvement of the regional climate models, the performance of regional climate change simulations, and the detailed assessment of the associated uncertainties.

The evaluation of the economic impacts will be based on representative case study regions located in the three CLAVIER countries Hungary, Bulgaria, and Romania shown in *Fig. 1*.

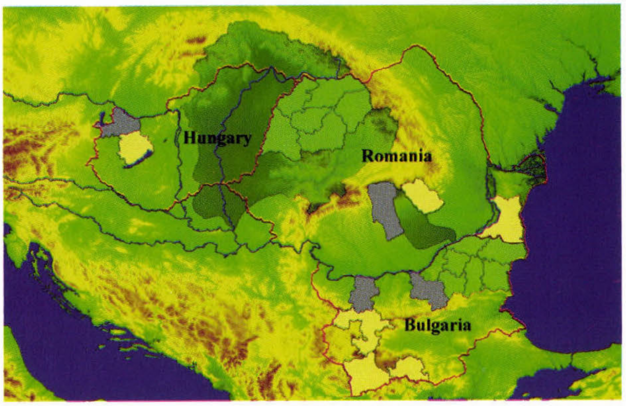

Fig. 1. CLAVIER case study regions for economic impact assessment (cyan: hydrological/water management; green: agriculture; gray: energy; yellow: tourism).

Table 1. List of CLAVIER project partners

Participant name	**Participant short name**	**Country**
Max-Planck-Institute for Meteorology, Hamburg	MPI-M	Germany
Hungarian Meteorological Service, Budapest	OMSZ	Hungary
University of Graz/Wegener Centre, Graz	WegCenter	Austria
Centre National de la Recherche Scientifique, Paris	CNRS	France
Joanneum Research, Graz	JR	Austria
VITUKI Environmental Protection and Water Management Institute, Budapest	VITUKI	Hungary
Budapest University of Technology and Economics, Faculty of Civil Engineering, Department of Hydraulic and Water Resources Engineering, Budapest	BME	Hungary
Env-In-Cent Consulting Ltd., Budapest	EiC	Hungary
National Institute of Meteorology and Hydrology, Sofia	NIMH	Bulgaria
University of National and World Economy, Sofia	UNWE	Bulgaria
National Institute of Hydrology and Water Management, Bucharest	INHGA	Romania
University of Cluj, Cluj	UBB	Romania
The Institute of Geography of the Romanian Academy, Bucharest	IG	Romania

To meet the project goals CLAVIER is split into a number of scientific objectives, for which work is carried out within 7 work packages. Researchers (*Table 1*) from 6 countries and different disciplines identify linkages between climate change and its impact on weather patterns with consequences on air pollution, extreme events, and water resources. A large effort is related to the first objective and includes modeling efforts on different scales, with different models, carried out by several partners. This paper will shortly introduce the modeling activities within CLAVIER, which will be presented in more detail in several other papers within this issue (*Szépszó* and *Horányi*, 2008). Here the focus will be on simulations from the regional climate model used at the Max Planck Institute for Meteorology. In addition, some general information about regional climate change in Europe, which has been achieved through regional downscaling of global IPCC AR4 simulations with the regional climate model REMO, will be presented. These simulations built the basis for more detailed investigations and first climate change assessments within CLAVIER.

2. The climate in the region

A whole suite of studies shows that the climate is already changing and various impacts are visible throughout the world (*McCarthy et al.*, 2001; *Voigt el al.*, 2004). The impacts on natural ecosystems and human health may be serious in the emerging but vulnerable regions in Europe, especially in CEEC. In Europe, 64% of all catastrophic events since 1980 are directly attributed to weather and climate extremes, and climate change projections show even an increasing likelihood of extreme weather events (i.e., *Voigt et al.*, 2004). The average annual length of the growing season in Europe has increased by about 10 days in the recent four decades and is projected to increase further in the future (*Voigt et al.*, 2004). As the annual air temperature increases in Europe, regional differences show that the temperature increase leads to warmer winters in the northeast part of Europe, while the southern part might face even warmer summers. Results from the PRUDENCE project (www.prudence.dmi.dk) show also a clear trend in annual precipitation, with a small increase in the North and a clear decrease in the southern regions of Europe, mainly in summer.

These results also point to the uncertainties, which are still included in climate change projections in CEE. A special model feature, that is typical for many regional climate models (RCMs) and to a less extent is visible in some general circulation models (GCMs), is the too dry and too warm simulation of climate over CEE during the summer (RAACS project; *Machenhauer et al.*, 1998). Their studies showed that this bias could not be explained by systematic errors in the large scale general circulation. In the MERCURE project (http://www.pa.op.dlr.de/climate/mercure.html), a follow-up of a RAACS, a major task was to understand and reduce or eliminate this model error, referred to as the summer drying problem (SDP). Here the Danube catchment was considered where the SDP is prominent. A major conclusion in MERCURE was that for three of five of the participating models, systematic errors in the dynamics appear which cause the SDP (*Hagemann et al.*, 2004). In the fourth RCM, deficiencies in the land surface parameterizations were mainly responsible for its SDP; while the fifth does not have a SDP. (This RCM is not a limited area model but a global model with a stretched grid that had a high resolution over Europe.) As the SDP seems to be related to the dynamics in several models, it was speculated that deficient features in the dynamic part of the fourth and fifth RCM may also exist, which are only overlaid by systematic errors in the surface parameterizations of these two models. Although the SDP was allocated to the representation of the dynamics in the RCMs, an exact cause of the problem was not found nor could it be eliminated. Following studies in the PRUDENCE project (*Christensen* and *Christensen*, 2007; *Jacob et al.*, 2007) have shown that the SDP still exists in 8 of 10 participating RCMs (*Hagemann* and *Jacob*, 2007). The ninth RCM is the stretched GCM mentioned before, and in the tenth RCM large overestimation of precipitation over the Danube catchment throughout most parts of the year might compensate any tendencies of erroneous drying of the area in its climate simulation. A summer warm bias (compared to CRU data: http://www.cru.uea.ac.uk/) over the Danube catchment is present for all 10 RCMs (*Hagemann* and *Jacob*, 2007). The SDP is a systematic bias in the simulation of today's mean climate, and several questions concerning their influence on extremes like floods, droughts, and their interaction with land use changes arise from it if the quality of current and future climate simulations is considered.

The summer drying problem is still an open issue strongly influencing the uncertainty related to climate change projections in CEEC. This issue as well as other factors determining the uncertainty in climate change projections will, therefore, be addressed within CLAVIER taking into account results from past and ongoing climate change investigations, like PRUDENCE and ENSEMBLES.

Within CLAVIER linkage between climate change and its impact on water resources is investigated. Ongoing and future climate changes are influencing the hydrological cycle and its variability as shown in many studies (e.g., *Hagemann* and *Jacob*, 2007; *Vidale et al.*, 2007). CEECs are especially exposed to changes in means and extremes of the hydrological cycle, e.g., changes in the water level of Lake Balaton or heavy precipitation events in the mountains of the Carpathian Range, which frequently lead to flash floods. Also the central and lower Danube basin ranks high on the world list of catchments exposed to flooding. Many of the streams have trans-boundary character what underlines the necessity to tackle these questions in a regional manner. The governments are planning measures to improve flood safety across CEE, and these efforts should be supported by reliable assessment of climate change induced modifications of flood hazard and flood risk.

Many regions of CEEC are surprisingly dry on the European scale; those are frequently exposed to droughts of short and long term (*Sharov* and *Koleva*, 1994). *Tran et al.* (2002) analyzed the relationship between atmospheric synoptic conditions over Europe and droughts in Bulgaria. *Szilagyi* and *Vorosmarty* (1997) analyzed the extreme groundwater depletion in the region along the central Danube. A clear connection between the atmospheric pattern and droughts is presented; however, Bulgarian droughts are influenced by even more features, thus many open questions have to be addressed. *Tran et al.* (2002) ask for more studies focusing on the impact of changes in atmospheric synoptic conditions and precipitation over the region. CLAVIER will address this issue and contribute to an improvement in the prediction of droughts in CEEC as well as to the investment of preparedness actions.

3. CLAVIER simulations

The issue of climate change uncertainties will be addressed through the multi-model and multi-scenario ensemble approach considering the three steps of the scenario production chain: greenhouse gas emission, climate scenario with coarse resolution global coupled climate model, and regionally-oriented high spatio-temporal resolution climate scenario. The regional climate models used within CLAVIER are REMO from MPI-M (*Jacob*, 2001), used in Version 5.7 by MPI-M and version 5.0 by the Hungarian Meteorological Service, and the LMDZ model, developed at CNRS in Paris (*Hourdin et al.*, 2006). The former is a limited-area model and the latter is a variable-grid atmospheric general circulation model with zoom over CEE. Data from two global climate models are used to drive and initialize the regional models. All three models use the ECHAM5/MPI-OM simulations performed for the 4th IPCC assessment report with a horizontal resolution of T63 (*Roeckner et al.*, 2006). In addition, the LMDZ model will be forced by boundary data with 2 to 3 degree resolution from the IPSL global model. For the greenhouse gas emission, the scenario is based on the IPCC A1B scenario mainly; additional simulations with the B2 scenario are available for the LMDZ model. Therefore, an ensemble of climate change simulations allows an advanced analysis of uncertainties.

The three regional climate models are used to simulate the climate evolution in CEE for the period 1951 to 2050, the future regional climate projection being the first half of the 21st century. The spatial resolution is around 20 km for most of the simulations, which are currently analyzed. A high resolution (10 km) transient scenario simulation with REMO5.7 is planned on the inner domain shown in *Fig. 2*, covering the CLAVIER target area. The regional modeling activities are carried out in four steps:

Assembling and assessment of existing climate scenarios for the region:
Several climate change simulations exist for CEEC carried out either in context of the IPCC report or within European projects, i.e., PRUDENCE, ENSEMBLES. These simulations are, however, not sufficient for advanced impact studies, due to either the too low spatial-temporal resolution, or the partial spatial coverage of our domain of interest.

Validation and adjustment of regional climate models:
Both regional models REMO and LMDZ, need to be adapted for the region. In particular, the elimination of the SDP is envisaged. Model parameters will be adjusted in order to break down the summer anticyclone blocking situation, which seems to be too persistent in this region.

Climate change simulations:

Once the regional models are validated, climate change simulations will be run from 1951 to 2050 at about 20 km and 10 km horizontal resolutions. The 20 km simulations are directly driven by the global model data, whereas the 10 km simulation will be performed in a two step double nesting approach, i.e., using the coarser regional model simulation results to initialize and drive the high resolution regional model simulation on 10 km.

Uncertainty due to internal variability of regional climate:

To further investigate the issue of regional climate change uncertainties, a new technique for quantification of the uncertainties related to model internal variability is being introduced within CLAVIER. A physical consistent perturbation technique of the lateral boundary data as well as the surface boundary data (as for example orography, albedo, or sea surface temperature) has been developed. Therefore, several RCM simulations can be carried out for one given set of forcing data (like global reanalysis data or global climate model output). The simulations are sensitive to the slightly perturbed data at the lateral and lower boundaries, and the differences between the individual runs can be attributed to internal variability. This technique is in a first step tested for single decades. In a second step the developed perturbation method will be applied for longer time periods in order to create an ensemble of simulations with one RCM (in this case REMO) for one forcing data set (in this case ECHAM5/MPI-OM). The results of this ensemble will be analyzed in order to quantify the uncertainty related to model internal variability. This approach is complementary to the multi-model and multi-scenario ensemble approach.

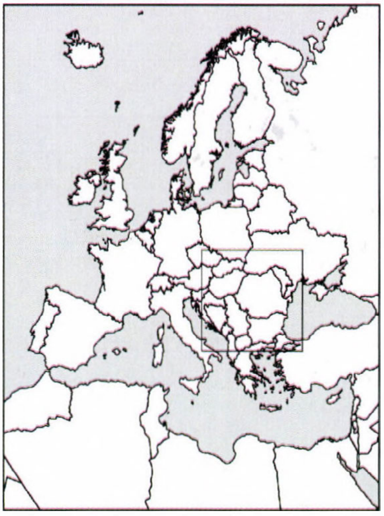

Fig. 2. Model simulation domain for the 0.22° (~25km horizontal resolution) domain. Inner box shows the CLAVIER target region.

4. Climate change in Europe

Within the last years, new global climate change simulations have been produced and published in the IPCC AR4 process. They have also been used for regional downscaling activities, which now provide new regional climate change signals, which are consistent with IPCC AR4 information. As an example, the horizontal pattern of possible climate change signals are shown using REMO5.7 results. Prior to the CLAVIER activities and in context of IPCC AR4, REMO was nested into the global climate model ECHAM5/MPI-OM developed and used at MPI-M. This means that at the lateral boundaries of the regional model domain, air masses are advected into the domain as they are calculated in the global model. Inside the regional model domain they are modulated through the influence of local and regional characteristics. Here REMO was used on a 50 km horizontal grid size for Europe, to analyze different developments of the climate change signals in different regions of Europe assuming an A1B scenario. All members of the ensemble of the A1B scenario, one A2 and one B1 scenario have been downscaled using the MPI-M modeling chain: ECHAM5/MPIOM and REMO5.7. Here only results from one A1B member (Nr. 1) are shown. A more detailed description and analyses of the climate signal are in preparation.

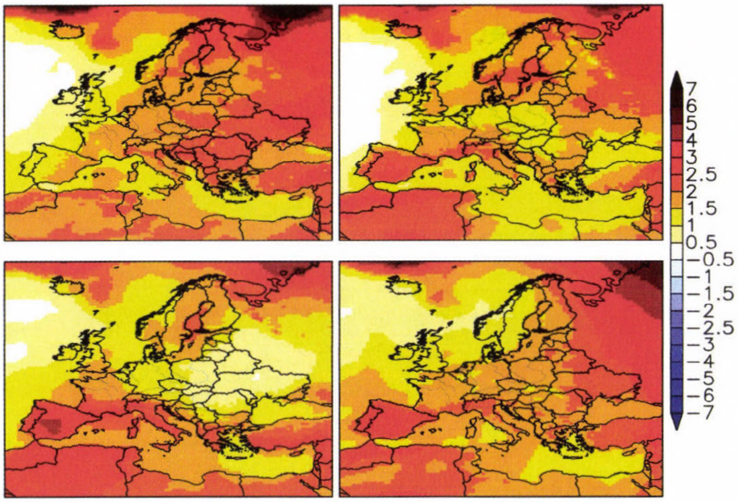

Fig. 3. Differences in the seasonal mean 2m air temperature [°C] around 2050 compared to the reference period 1961–1990. Winter (upper left), spring (upper right), summer (lower left) and fall (lower right).

Fig. 3 shows the change in 2m air temperature for Europe, which is regionally very different. Until 2040–2050 an increase in summer temperatures (*Fig. 3*, lower left) of more that 2.5 °C compared to 1961–1990 is calculated for the south part of France, Spain, and Portugal, while in most parts of Central Europe less than 1 °C increase is projected. In winter (*Fig. 3*, upper left) the simulated increase in temperatures is about 1.5 °C to 2 °C and covers an area from Scandinavia to the Mediterranean. Only in those regions, which are directly influenced by air masses from the Atlantic Ocean, like Great Britain, Portugal, and parts of Spain, a less strong increase is simulated.

The changes until 2100 are displayed in *Fig. 4*. Here a strong warming of more than 3 °C for the entire European region is visible in summer and winter seasons.

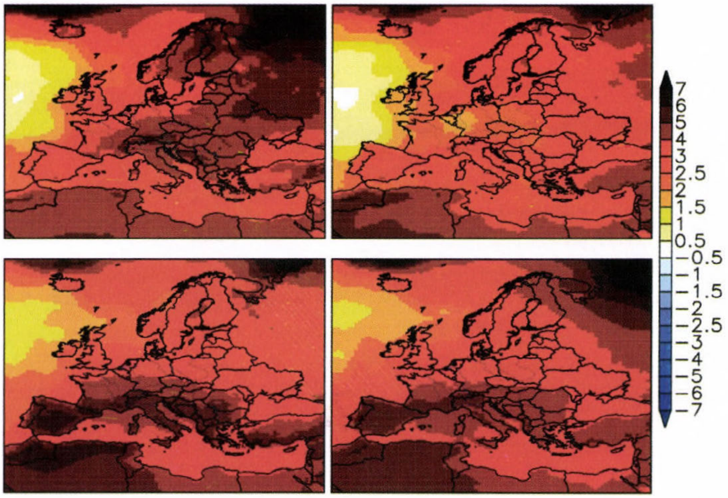

Fig. 4. Differences in the seasonal mean 2m air temperature [°C] around 2100 compared to the reference period 1961–1990. Winter (upper left), spring (upper right), summer (lower left) and fall (lower right).

At the same time, changes in precipitation pattern are projected. Until the middle of this century (~2050, *Fig. 5*) a clear decreasing trend of about 50% and more is calculated for the Mediterranean region in all seasons. Scandinavia might face more precipitation than today, especially in winter. During summer months precipitation seems to decrease with more than 30% in Great Britain. These changes are most likely related to an extension of the Azores High, which stretched further northeast into parts of Western Europe. The simulated pattern changes are developing further until 2100 (*Fig. 6*), with precipitation decreases in summer up to the southern part of Scandinavia.

For the CLAVIER region (as well as for the entire Europe) a strong warming is projected, which needs to be considered in view of the well-known SDP. Associated with the warming, a dividing line between areas with precipitation increase and decrease is calculated. The position of this line is still very difficult to project and its location can vary with emission scenarios or models under consideration. Therefore, CLAVIER emphasizes model validations and aims to analyze the robustness of the climate change signals from different simulations in the CLAVIER region.

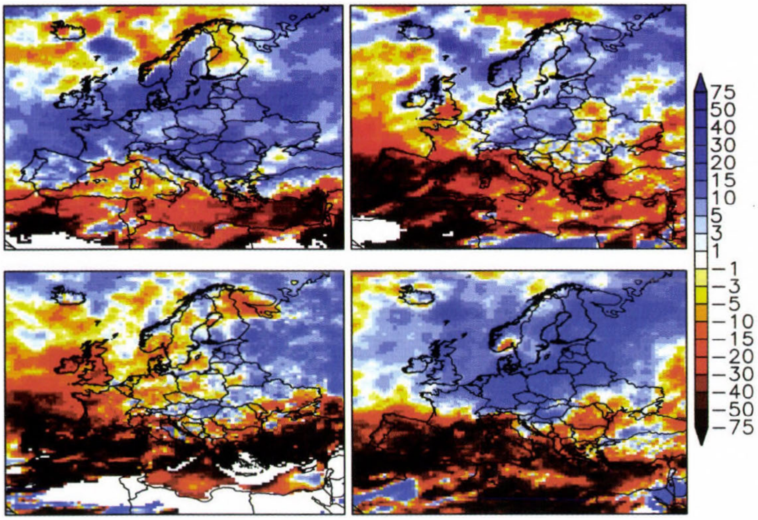

Fig. 5. Differences in the seasonal precipitation [%] around 2050 compared to the reference period 1961–1990. Winter (upper left), spring (upper right), summer (lower left) and fall (lower right).

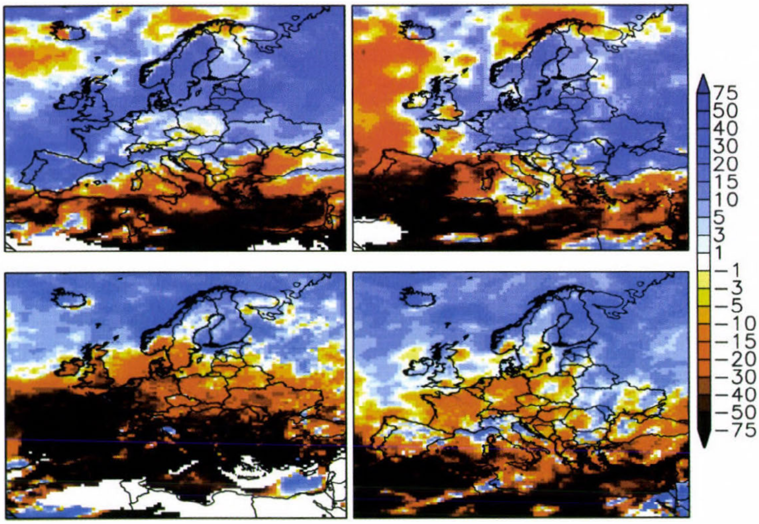

Fig. 6. Differences in the seasonal precipitation [%] around 2100 compared to the reference period 1961–1990. Winter (upper left), spring (upper right), summer (lower left) and fall (lower right).

5. *Validation of model performance in the CEEC region*

The CLAVIER project is still ongoing, therefore, results of the model validation will be shown exemplarily for the MPI-M REMO5.7 simulations. Similar work is done for the LMDZ model and for the REMO5.0 simulations done at the Hungarian Meteorological Service.

To assess how well the REMO model is suited to simulate the climate in Central and Eastern Europe, a validation based on a REMO simulation with a horizontal resolution of 0.22° driven by ECMWF ERA-40 reanalysis data has been performed. Initializing and forcing the regional model with reanalysis data ensures that the model results represent the real observed climate in the best possible way. These kinds of model simulations are thus well suited for a detailed comparison to meteorological observations. The model domain is shown in *Fig. 2*, where the small inner box denotes the area used for the evaluation. The model simulation covers the whole ERA-40 period from 1958 to 2001. For the analysis, seasonal mean values of simulated temperature and precipitation for a 20-year period from 1960 to 1979 have been compared to observed values. The observational dataset used was a gridded dataset of daily temperature and precipitation provided by the ENSEMBLES project (*Haylock et al.*, 2007).

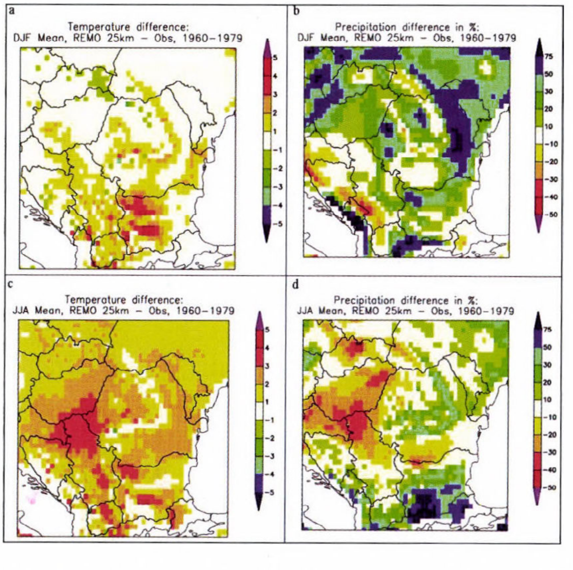

Fig. 7. Difference between REMO-ERA-40 simulation and ENSEMBLES observations for temperature [°C] (a, c) and precipitation [%] (b, d), for winter (upper panels) and summer (lower panels).

Fig. 7 shows the deviations between simulated and observed 20 year mean winter and summer temperature and precipitation. For temperature (*Fig. 7a, c*) a warm bias of the model can be seen, which is larger in summer than in winter, and which is typical for the above mentioned summer drying problem. Associated with the summer warm bias there is a dry bias shown in *Fig. 7d*. The summer dry bias is prevalent in the lower regions, whereas precipitation in higher elevations is overestimated by the model (e.g., over the Carpathians and the mountain areas of Pirin, Rila, and Rhodopes in Bulgaria). Winter precipitation seems to be overestimated by the model in most regions (*Fig. 7b*). Part of the differences in winter precipitation, especially in mountainous areas might be related to a systematic underestimation of snow in the observational dataset, which is known as undercatch the measuring gauge, and which can be as large as 30 to 50% of the actual solid precipitation (e.g., *Frei* and *Schär*, 1998; *Fassnacht*, 2004). The warm bias and the underestimation of summer precipitation by the model are a substantial part of ongoing model development in the CLAVIER project.

6. Conclusions

The validation of the REMO model for the Central and Eastern European region revealed that the summer drying problem known from previous modeling studies like MERCURE and PRUDENCE is still present in actual REMO simulations. The knowledge of such model biases is indispensable for the assessment of climate change impacts. The CLAVIER strategy to deal with the known model deficiency is firstly to examine the possible reasons for the SDP in detail in order to improve the responsible part of the model physics/dynamics. Secondly, existing biases have to be communicated to the users of the climate model data and solutions have to be provided to cope with the known uncertainties. This is especially important in a multidisciplinary climate change impact assessment project, like CLAVIER. For the CLAVIER project this means that the climate change information are provided as 'delta change approach', i.e., only changes of climatic variables are considered, not the absolute values calculated by the model. This approach is based on the assumption that model biases do not change under climate change conditions. In case that absolute values are inevitable, e.g., for the calibration of impact models, a bias correction based on observational data will be performed. Currently, the climate change simulations are in progress and first results are analyzed and distributed to CLAVIER partners.

Acknowledgments—We acknowledge the climate dataset from the EU-FP6 project ENSEMBLES (http://www.ensembles-eu.org) and the data providers in the ECA&D project (http://eca.knmi.nl). We also thank *Holger Göttel* for providing Figs. 3 to 6.

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Validation of the ALADIN-Climate regional climate model at the Hungarian Meteorological Service

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Abstract—Regional climate models are popular and efficient tools for the assessment of the regional aspects of the past and future climate. The application of such models is indispensable for the provision of climate simulations over a smaller region, such as Hungary. The ALADIN-Climate regional climate model was adapted by the Hungarian Meteorological Service in order to derive a regional climate model which can be used efficiently for climate change simulations over Hungary. In this paper three different recent past (1961–2000) regional climate simulations are examined and evaluated: the ERA-40-driven 10 km and 25 km resolution simulations and the ARPEGE-driven 10 km resolution simulation. Based on these investigations, the strengths and weaknesses of the simulations are analyzed in detail in order to understand the behavior and reliability of the ALADIN-Climate model for the past climate. Also, some examination regarding the sensitivity of the model with respect to the domain size and resolution was undertaken. It was demonstrated to what extent the model is capable of simulating the statistical characteristics of the climate for a 30-year period. The results obtained suggest: (1) the ALADIN-Climate model driven by ERA-40 "perfect" lateral boundaries is colder and wetter than reality for the period of 1961–1990, (2) the integration driven by the ARPEGE model slightly improved the results and, furthermore, (3) provided added value to the global model's results. Additionally it was found that (4) the 25 km simulation on a larger domain provided better results than the 10 km one using a smaller domain, which can be attributed to the fact that 10 km domain is overly small. The results also (5) justify the application of the ALADIN-Climate model for climate change scenario experiments for Hungary.

Key-words: regional climate modeling, ALADIN-Climate model, dynamical downscaling

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1. Introduction

The demand for more spatially and temporally detailed weather and climate information is continuously increasing. This requirement, together with the increased availability of computer power, led to the application of more highly resolved models from the nowcasting to the climate ranges. As far as climate modeling is concerned, global and regional climate models are widely used for the simulation of the past and the future evolution of the climate system. There are three tools that have been successfully applied to bridge the gap between the low resolution global climate models and the regional and local characteristics: variable-resolution global models, statistical downscaling, and dynamical downscaling with regional climate models (RCMs). The first method allows the production of higher resolution climate information without too much additional investment in computer power with respect to the "usual" global simulations (*Brankovic* and *Gregory*, 2001; *May* and *Roeckner*, 2001; *Duffy et al.*, 2003; *Coppola* and *Giorgi*, 2005). Statistical downscaling consists of establishing statistical relationships between large scale (global) parameters as predictors and regional (local) parameters as predictands. These relationships are then applied to the global model outputs (*Kattenberg et al.*, 1996; *Hewitson* and *Crane*, 1996; *Wilby et al.*, 2004) and results in information on a regional scale. RCMs, as limited area models, cover only a portion of the planet, typically a continental or even smaller domain (*Giorgi* and *Mearns*, 1991; *McGregor*, 1997; *Giorgi* and *Mearns*, 1999; *Wang et al.*, 2004). They require lateral boundary conditions (LBCs) obtained from "observations", such as atmospheric analyses (*Uppala et al.*, 2005), or global simulations. The principal reason for performing regional simulations is to successfully simulate such regional characteristics which are "out of the reach" of the global models, therefore, providing added value through more precise representation of the different surface features, the application of the higher resolution dynamics and improved physical parameterizations.

The ALADIN limited area numerical weather prediction model (*Horányi et al.*, 1996; *Horányi et al.*, 2006) has been developed through an international cooperation and is one of the widely used limited area models in Europe. The ALADIN spectral model family is a very useful tool not only for short range weather prediction, but also for climate range simulations because of its particularly high computational efficiency. Firstly, the original short range version of the model was studied in order to check whether any spurious accumulation of systematic errors (biases) could be detected for longer integrations – it was found not to be the case (*Janisková*, 1994). Later the ALADIN-Climate model had been created by merging the physical parameterization package of the ARPEGE-Climat global climate model and the dynamics of the ALADIN model. This model was successfully adapted by the Hungarian Meteorological Service in 2005, and it has been used for various climate experiments. Within that framework some shorter time range (3–5 years) experiments have been carried out in order to establish the most appropriate model version, the model domain, the horizontal resolution, and the spin-up time before committing to the first longer time period experiments. This first long-term experiment (1958–2000) has been performed by the Hungarian *National Climate Dynamics Programme* (*www.met.hu/palyazat/nkfp_klima2005.php*), and the second one, at a higher horizontal resolution, within the framework of the *CECILIA* (*Central and Eastern Europe Climate Change Impact and Vulnerability Assessment*) project (*www.cecilia-eu.org*).

In Section 2 a brief description of the ALADIN-Climate model is given. Section 3 introduces the model experiments, the evaluation methods, and the observational data used in the present work. Results are presented in Section 4 and the conclusions are drawn in Section 5.

2. The ALADIN-Climate model

The ALADIN-Climate model has been created with the combination of the ALADIN model's dynamics and the ARPEGE-Climat global model's physics. The ARPEGE-Climat global model has been constructed with the relevant modifications of the physical parameterization package of the ARPEGE/IFS global model (*Courtier et al.*, 1991). The ALADIN model is a spectral limited area model developed for short-range regional weather forecasting (*Horányi et al.*, 1996). Likewise the "mother" system of the ALADIN model is ARPEGE/IFS, the ALADIN-Climate's one is ARPEGE-Climat.

For the sake of completeness it has to be mentioned here that in most applications of the ALADIN model the initial and lateral boundary conditions are obtained by interpolation from the ARPEGE analysis and forecast fields. Horizontally, the model domain represents a rectangular area with uniform spacing between the grid points in both horizontal directions. Usually the tangent version of the Lambert conformal projection is used. The vertical coordinate system is a pressure-based hybrid-eta – terrain-following near the ground and converging towards a pressure-type system close to the model top (*Simmons* and *Burridge*, 1981). The model dynamics are based on the non-linear hydrostatic primitive equations. The time integration of the model includes a semi-implicit treatment of fast-propagating waves combined with the application of a semi-Lagrangian advection scheme. All of this allows a significantly larger time step to be used due to the weakened numerical stability criteria obtained in the two-time-level semi-implicit semi-Lagrangian scheme. The large scale meteorological information is imposed on the inner model solution by a classical relaxation scheme (*Davies*, 1976). With the application of an additional relaxation zone, the method is also capable of damping the artificial reflection and transmission of small scale waves on the boundaries of the domain of interest. Model prognostic variables are zonal and meridional wind components, temperature, specific humidity, and surface pressure.

The physical parameterization package of the ALADIN-Climate model largely corresponds to the physics of the ARPEGE-Climat global model. It uses the Fouquart and Morcrette radiation scheme (FMR), which follows the concept of *Morcrette* (1989) and is based on the ECMWF model including the effects of the greenhouse gases and direct effects of aerosols based on Tegen monthly climatology. As for the land-scheme, the ALADIN-Climate model applies the ISBA (*Interaction of Soil Biosphere Atmosphere*) scheme (*Noilhan* and *Planton*, 1989), which involves four soil temperature layers without a deep relaxation, two soil moisture layers, and a single layer snow model with variable albedo and density based on *Douville et al.* (1995). The deep convection scheme follows *Bougeault* (1985), but unlike the short range version of the model, it excludes the entrainment and detrainment profiles from the description of convective precipitation processes. *Ricard* and *Royer*'s scheme (1993) is used for cloudiness and *Smith*'s scheme (1990) for large scale precipitation.

3. Experiments and evaluation

The basic objective of the recent work is to understand and assess the behavior of the ALADIN-Climate model regarding its ability to represent the climate of the recent past. Without such thorough testing the model cannot be used for providing climate simulations for the future (although the validation information based on the simulations of the past cannot be directly and explicitly applied for the "bias correction" of the scenario integrations). For this kind of evaluation, the most common approach is to integrate the model over a recent, sufficiently long period (e.g., 40 years) using "perfect" lateral boundary conditions, such as the ERA-40 dataset derived at ECMWF (*Uppala et al.*, 2005). It is noted here that the ERA-40 data are certainly not perfect in every sense – they have their own deficiencies as well (*Simmons et al.*, 2004; *Hagemann et al.*, 2005). However, they do provide one of the best estimates of the past and present climate. Furthermore, during the ERA-40-driven model integrations (due to the differences between the derivation of the ERA-40 data and the internal dynamics and physics of the ALADIN-Climate model) some unbalances might occur, arising from the boundary conditions. Nevertheless, in spite of these deficiencies, the ALADIN-Climate model integration driven by the ERA-40 data is considered to be a reliable solution for the application of the model in reproducing the recent past climate over our domain of interest.

Two model domains and resolutions were defined: a larger domain with 25 km horizontal resolution and a smaller one with 10 km resolution, both with 31 vertical levels. The domains and their orography are shown in *Fig. 1*. Both domains were used for model integrations between 1958 and 2000, where the first three years were considered as the spin-up period, therefore, the results were evaluated only for the period 1961–2000. The smaller 10 km resolution domain was used to assess the impact of the resolution increase and domain changes as compared to the coarser resolution and larger domain integrations. A third simulation was carried out with the smaller domain for the period of 1960–1990. This integration was driven by the ARPEGE-Climat model. It is noted here that the ARPEGE-Climat boundary conditions are in much better physical and dynamical consistency with the ALADIN-Climate model, than the ERA-40 data. The ARPEGE-Climat model has a variable resolution being around 50 km over Southern Europe, decreasing to 300 km at the antipode (*Table 1*).

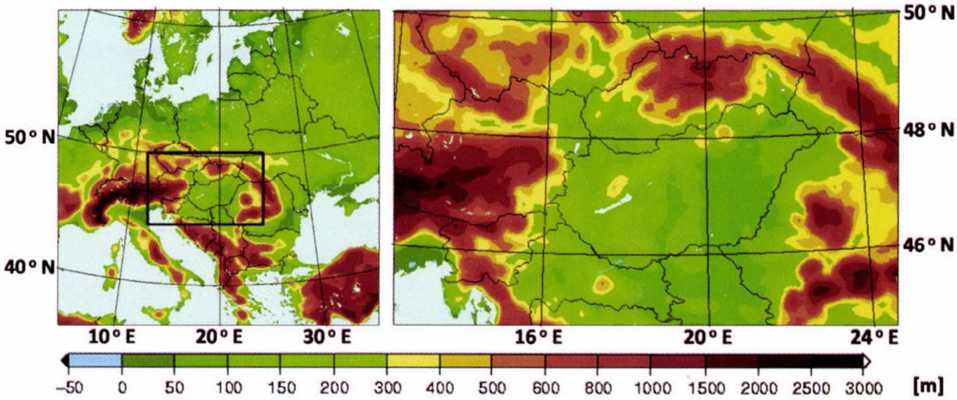

Fig. 1. The ALADIN-Climate model domain and orography for the 25 km (left) and 10 km (right) integrations.

The drawback in applying the ARPEGE-Climat model as lateral boundary condition is that it is also a simulation, which might have biases with respect to the real climate. Therefore, it is worth checking how the "perfect, but inconsistent" and the "simulated, but consistent" boundary conditions compare for the same limited area model integration. Two factors should be kept in mind while considering the length of the spin-up period for the ALADIN-Climate simulations driven by the ARPEGE-Climat model: the global lateral boundary conditions are already in good dynamical and physical balance; and there are similarities (in terms of dynamical core and physical parameterizations) between the global and limited area models. Therefore, the spin-up period for this integration was shorter than was the case for the ERA-40 run. In practice, this means that for the 1960–1990 integrations just the first year was considered as spin-up time and the 1961–1990 classical reference period was used for the evaluation. In spite of the difference in spin-up periods, it is believed that the different model simulations are fully comparable.

Table 1. Basic characteristics of the different integrations analyzed

Short name referred to in this paper	Domain	Horizontal resolution (km)	Vertical levels	Timestep (minutes)	Initial and lateral boundary conditions
ALADERA_25	lat: 35.8 – 59.3°N lon: 4.8 – 44.1°E	25	31	15	ERA-40
ALADERA_10	lat: 44.6 – 50.0°N lon: 12.4 – 25.2°E	10	31	6	ERA-40
ALADARP	lat: 44.6 – 50.0°N lon: 12.4 – 25.2°E	10	31	6	ARPEGE-Climat
ARPEGE	global model	50	31	30	–

During the evaluation the different integrations are inter-compared to each other and also compared to different observational datasets (*Table 2*). These observational data comprise both the widely used *Climatic Research Unit* (CRU) dataset (*New et al.*, 2000; *Mitchell* and *Jones*, 2005) and the *Hungarian gridded dataset* (HUGRID). The CRU data (*www.cru.uea.ac.uk*, produced by the University of East Anglia) were applied at a resolution of 10 arc minutes (CRU10, *Mitchell et al.*, 2004). HUGRID was created at the Hungarian Meteorological Service by the Meteorological Interpolation based on Surface Homogenized Data Basis (MISH) method (*Szentimrey et al.*, 2005), which was developed for the spatial interpolation of different conventional meteorological observations. These data are available for the Hungarian territory with 0.1 degree latitude-longitude resolution.

Table 2. Characteristics of the different observational data used

	Domain	Resolution
CRU10	lat: 34.0 – 72.0°N lon: 11.0°W – 32.0°E	10 arc minutes
HUGRID	lat: 45.7 – 48.6°N lon: 16.0 – 23.0°E	0.1 degree

It is important to note that for the production of the ARPEGE-Climat model driving fields for the ALADIN-Climate model, an interpolation has been done from the global resolution to the resolution of the ALADIN-Climate model (10 km). This interpolation is performed on anomaly values, where explicitly the differences between the ARPEGE-Climat model and the surface climatic values (for instance orography, albedo, emissivity, land-sea mask, etc.) of the global model are considered. After interpolation to the target grid (in this case to 10 km), the interpolated anomaly values are added to the higher resolution surface climatic values provided for the regional climate model. Based on this method, the information of the coarse resolution (50 km) global model (projected to the regional one) also reflects high-resolution surface properties, such as higher mountains or the areas around big lakes, for example.

The evaluations are carried out through the assessment of deviations from the observations, and additionally, systematic errors and root mean square errors (RMSE) are computed. With reference to RMSE it is already anticipated here that the RCMs cannot be expected to simulate the time series of annual or seasonal means if the driving data are given by global climate model – and not a re-analysis database – since the global models are unable to provide information on individual years. The global and regional climate models are expected to simulate only the long term inter-annual variability and the average behavior of the climate system on a longer time scale (30–40 years). Consequently, it is not expected that results in terms of RMSE, the frequency distributions of the parameters or the temporal evolution charts, would be as good as those from the ERA-40-driven cases. It is also noted that the 2D-map evaluations (patterns) are computed over the domain of the 10 km resolution model, and all the other evaluations (tables, time evolution and frequency distribution figures) are made on the Hungarian territory.

4. *Results*

4.1. 2m temperature

It can be clearly seen (*Fig. 2*) that the models have systematic underestimation with respect to the CRU10 dataset. This temperature underestimation is generally 1–3 °C in the ERA40-driven cases (ALADERA_25 and ALADERA_10) and around 1 °C in the ARPEGE-driven (ALADARP) case and in the ARPEGE-Climat (ARPEGE) global model itself.

Looking at the results in detail, the simulations are always closer to the observations in the area of the Carpathian Basin – which is a relatively flat terrain – than in the higher mountains. Additionally, for the 10 km simulations the biggest systematic errors arise near to the model boundaries. The errors in the Alpine region are considerable in all simulations. This is attributed not only to the impact of the model boundaries (though the error is largest in the case of the 10 km simulations, where the model boundaries are near to the high mountains) but also to the orography mis-representation within both the models and the observational data sets.

Focusing only on the basin area, particularly over Hungary, the global and the ARPEGE-driven simulations are the closest to the observations – the underestimation remains under 1 °C over the largest part of the Hungarian territory. On the other hand, slight overestimation seems to occur in the eastern part of the basin, on the Great Hungarian Plain (see *Fig. 3*, where the eastern part of Hungary is zoomed and another color palette is used). This characteristic feature of the global model, as can be seen later, remains the same in the different seasons, i.e., the ARPEGE global model is relatively warm in the Great Hungarian Plain, compared to the observations. Surprisingly, the results of the ERA-40-driven simulations are rather different from each other; the higher resolution results are more biased in general, particularly near the edges of the high resolution model domain but also over Hungary, where the underestimation is more conspicuous for the 10 km simulation. The difference between the two simulations is around 1 °C in the Hungarian territory.

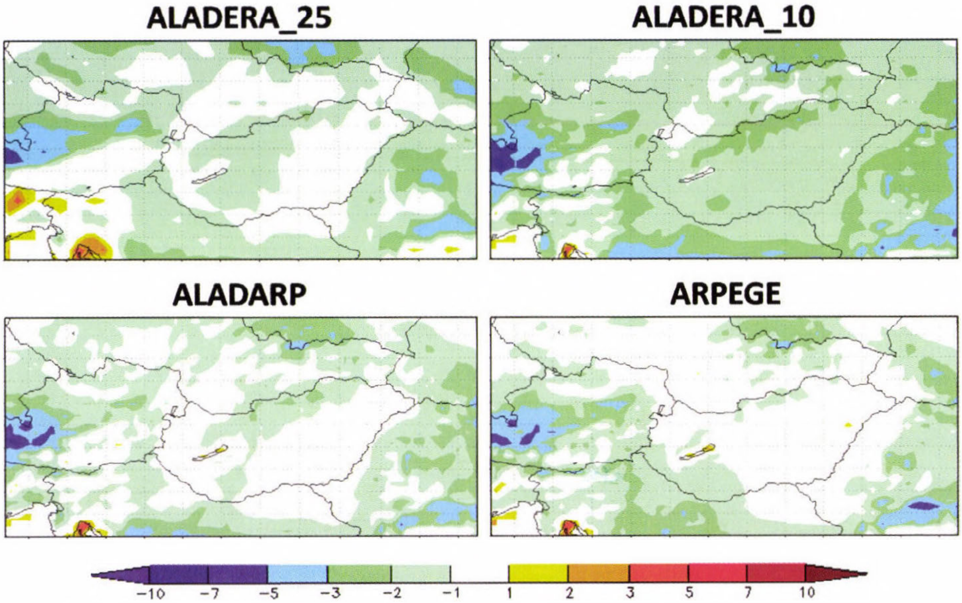

Fig. 2. Difference of annual mean temperatures (model simulation – CRU10 [°C]) for the period of 1961–1990 for ALADERA_25, ALADERA_10, ALADARP, and ARPEGE.

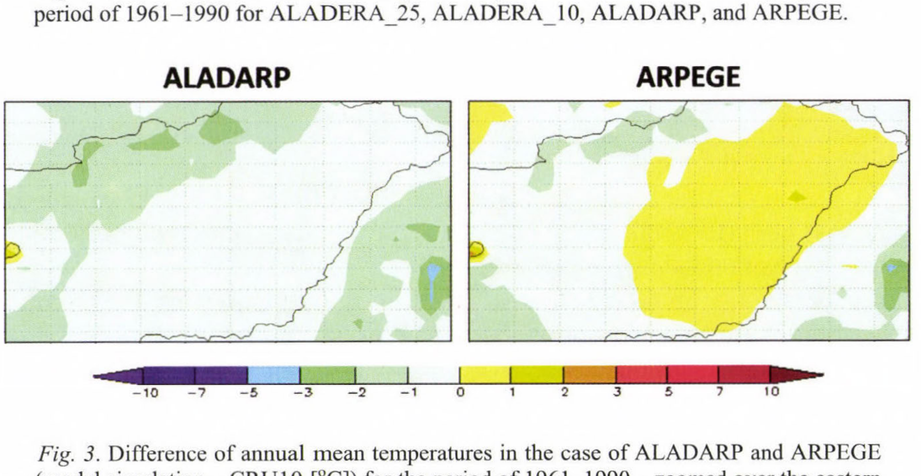

Fig. 3. Difference of annual mean temperatures in the case of ALADARP and ARPEGE (model simulation – CRU10 [°C]) for the period of 1961–1990 – zoomed over the eastern part of Hungary.

Regarding the seasonal mean temperature difference fields (*Fig. 4*) in general, the simulations are colder than the observations in the transitional seasons (spring and autumn), and are, with some exceptions, rather near to the observations in summer and winter. The systematic underestimation exceeds 5 °C in some mountainous regions and even 7–10 °C in the Alps during the transitional seasons.

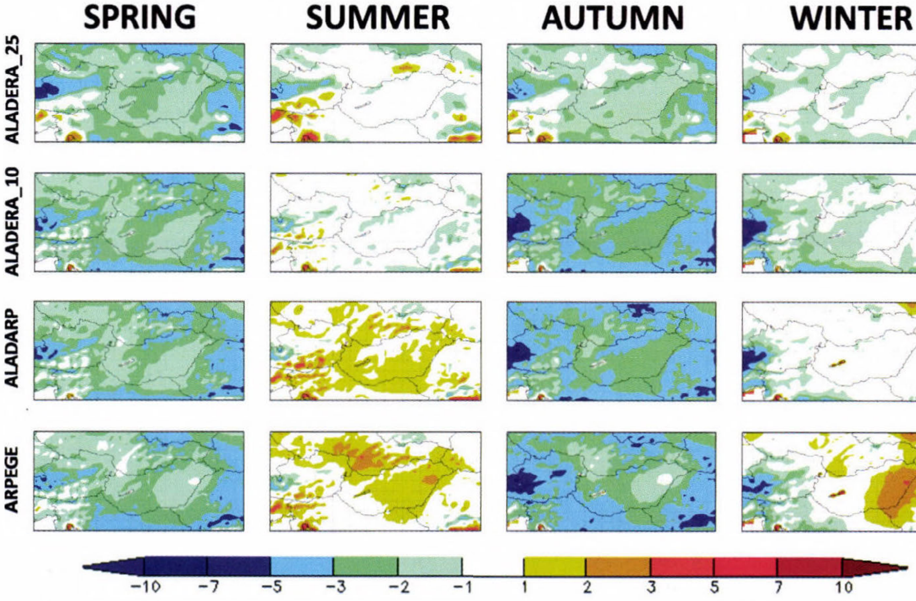

Fig. 4. Difference of seasonal mean temperatures (model simulation – CRU10) [°C]) for the period of 1961–1990 (from the top to the bottom: ALADERA_25, ALADERA_10, ALADARP and ARPEGE).

Probably due to the deficiencies of the observation datasets in the high mountains and the negative impact of the model boundaries, as in the annual case, the estimations are always closer to the observations in the fairly flat Carpathian Basin, than in the higher mountainous areas. Moreover, the biggest errors occur again near to the model boundaries in the 10 km simulations. Curiously, in the case of the ARPEGE-Climat global model (which does not suffer from any lateral boundary problem), similar large errors can also be seen at the edges of the 10 km domain, mainly in the high mountains. This is probably due to the inaccurate description of the orography.

Concentrating only on the basin area, all of the simulations give similar results in spring: the underestimation of temperature is higher than the annual systematic error; it is between 1 and 2 °C on the plains and 2–3 °C in the hills. The 25 km simulation in autumn shows relatively similar results to spring but, unexpectedly, the 10 km simulations have an even bigger negative bias. These significant underestimations in the transitional seasons cause a slight annual negative bias in the majority of the model versions examined, even if the other seasons show positive biases. The ERA-40 forced versions are fairly unbiased during the summer – the underestimation exceeds 1 °C only in the Hungarian mountains. However, 1–2 °C overestimation can be seen in the ARPEGE and ALADARP integrations. Due to this summer overestimation, the ARPEGE-driven case and the global model have smaller annual systematic errors (almost unbiased) than the ERA-40-driven versions. While the ERA-40-driven versions are closer to the observations in summer than in winter, the ALADARP is almost perfectly unbiased in winter, and it has a relatively big overestimation in summer. The disagreement between the ARPEGE-driven ALADIN-Climate model and its driving model is largest in the coldest season. While the regional model has practically no bias, the systematic errors of the ARPEGE-Climat model exceed 2–3 °C in the eastern part of Hungary. If the difference maps of the ARPEGE-Climat model are studied more carefully, it can be seen that it has relatively large systematic errors throughout the year; however, these biases have different signs (as will be shown later, where the systematic errors are quantified) and compensate for each other during the year resulting in a rather good annual performance (*Fig. 2*). On the other hand, the "always relatively warmer" Great Hungarian Plain in the driving model decreases the bias of the model over the domain in spring and autumn, and increases it, by about 2–3 °C, in summer and even more in winter.

The systematic errors given in *Table 3* objectively quantify the evaluations based on *Figs. 2–4* for the Hungarian area. Annually, the ERA-40-driven model versions have bigger systematic errors than the global and the ARPEGE-driven ones. As mentioned above, the smallest annual bias can be found in the ARPEGE-Climat model. Although it has the coarsest horizontal resolution and the systematic errors are relatively large in every season, the biases with different signs compensate each other. The ERA-40-driven cases are better, particularly during the summer. Surprisingly, the performances of the two ERA-40 simulations are rather different in terms of bias especially in autumn, when the ALADERA_10 simulations are systematically worse than those of the ALADERA_25. The global model has a bias one order of magnitude larger than that of the driven ALADIN-Climate version for winter. As indicated earlier, the global model, throughout the year, simulates the temperature field of the Great Hungarian plain with a much larger warm bias than in other areas of the domain. This is also true when compared to the other model versions. These relatively large positive errors during summer and winter in the eastern part of Hungary cause bigger biases for the ARPEGE than in the case of ALADARP. Though it can be expected that the limited area model improves the simulations of the global model by the coupling, it is not certain that the desired "added value" is the only answer for this significant difference. While the size of the errors is bigger in the transitional seasons in all of the model cases examined, the differences between the simulations are much larger in summer and winter; on the other hand, the models are very close to each other in spring and autumn.

The results of the models compared against CRU10 are similar to those against the Hungarian gridded dataset. The small differences can be explained by the different resolution of the two observational datasets. The differences between the two datasets are particularly emphasized in the mountainous areas, where the temperatures are lower in the HUGRID data. Consequently, when the models have negative systematic errors compared to the CRU10 dataset, the absolute values of the errors are slightly decreased with respect to the HUGRID data.

Table 3. Systematic errors of annual and seasonal simulated temperature fields against the CRU10 and the HUGRID data in the case of ALADERA_25, ALADERA_10, ALADARP, and ARPEGE experiments, in the area of Hungary for the period of 1961–1990

Temperature bias [°C]	**Annual**	**Spring**	**Summer**	**Autumn**	**Winter**
ALADERA_25 – CRU10	–1.05	–1.99	–0.25	–1.61	–0.66
ALADERA_10 – CRU10	–1.50	–2.12	–0.60	–2.66	–0.88
ALADARP – CRU10	–0.80	–2.01	1.06	–2.69	0.11
ARPEGE – CRU10	–0.37	–1.91	1.29	–2.27	1.11
ALADERA_25 – HUGRID	–0.89	–1.84	–0.13	–1.14	–0.36
ALADERA_10 – HUGRID	–1.41	–2.05	–0.56	–2.28	–0.72
ALADARP – HUGRID	–0.72	–1.94	1.10	–2.31	0.27
ARPEGE – HUGRID	–0.29	–1.83	1.32	–1.89	1.27

Table 4. Root mean square errors of annual and seasonal simulated temperature fields against the CRU10 and the HUGRID data in the case of ALADERA_25, ALADERA_10, ALADARP, and ARPEGE experiments, in the area of Hungary for the period of 1961–1990

Temperature RMSE [°C]	**Annual**	**Spring**	**Summer**	**Autumn**	**Winter**
ALADERA_25 – CRU10	1.12	2.05	0.80	1.71	1.71
ALADERA_10 – CRU10	1.55	2.17	0.89	2.71	1.26
ALADARP – CRU10	1.15	2.34	1.80	3.22	2.33
ARPEGE – CRU10	1.06	2.26	1.85	2.95	2.74
ALADERA_25 – HU	0.97	1.90	0.78	1.26	1.01
ALADERA_10 – HU	1.46	2.09	0.83	2.33	1.17
ALADARP – HU	1.13	2.31	1.82	2.95	2.37
ARPEGE – HU	1.08	2.23	1.89	2.72	2.82

In order to get a deeper insight into the behavior of the regional climate simulations, it is not sufficient to focus only on the systematic errors, since large errors of opposite sign may compensate each other resulting in a perfectly unbiased – though far from accurate – model. For instance, within the ALADERA_25 and ALADERA_10 simulations, underestimation (negative bias) occurs in every season and, therefore, the annual bias is a relatively large negative value. On the other hand, for ALADARP the bias is changing its sign across the seasons resulting in a smaller annual bias value. Indeed, if the root mean square errors (RMSE, *Table 4*) are examined, then (for instance) the ALADERA_25 and the ALADARP annual values are rather near to each other, in spite of the fact that the bias characteristics were better for ALADARP.

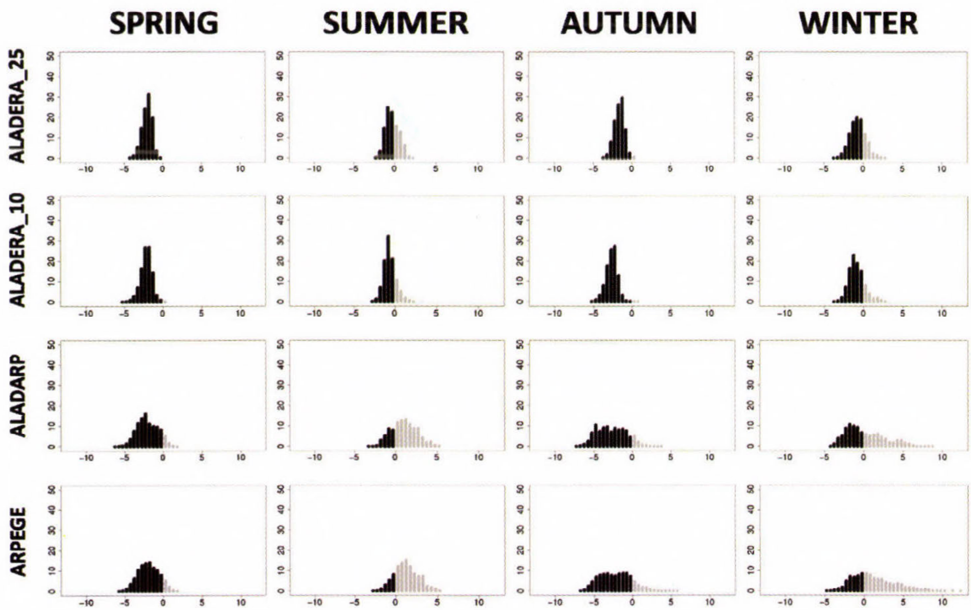

Fig. 5. Frequency distribution of seasonal temperature differences with respect to CRU10 data for ALADERA_25, ALADERA_10, ALADARP, and ARPEGE simulations. X axis: temperature difference [°C] in the range of [–10, +10]. Y axis: frequency [%] in the range of [0, 50] (gray: positive bias, black: negative bias).

Fig. 5 shows the relative frequency distributions of the seasonal temperature systematic errors, specifically, the distribution of the different amplitudes of the systematic errors, measured year by year and gridpoint by gridpoint in the different seasons. These plots indicate the amount of the positive (gray) and negative (black) biases during the 30 years in the different seasons. For these kinds of diagrams the bias is optimal if the histograms are symmetric around the zero line (the total area of the gray and black columns are the same). In those model cases, where the graph of the distribution function of the frequency is relatively narrow and high, and naturally the peak is not too far from the zero x coordinate, the RMSE is reasonably low. Where the graph is wide and low, even if the area of the positive and negative biases are the same (that is the bias of the whole period is close to zero), the RMSE is considerably high.

These kinds of charts are based on the year by year biases. The global model driven cases (and the global models themselves) are not expected to simulate the time evolution of the atmosphere during the examined period (see explanation above). Therefore, unsurprisingly, the range of the differences is much wider in the case of ALADARP and ARPEGE, than that in the ERA-40-driven cases.

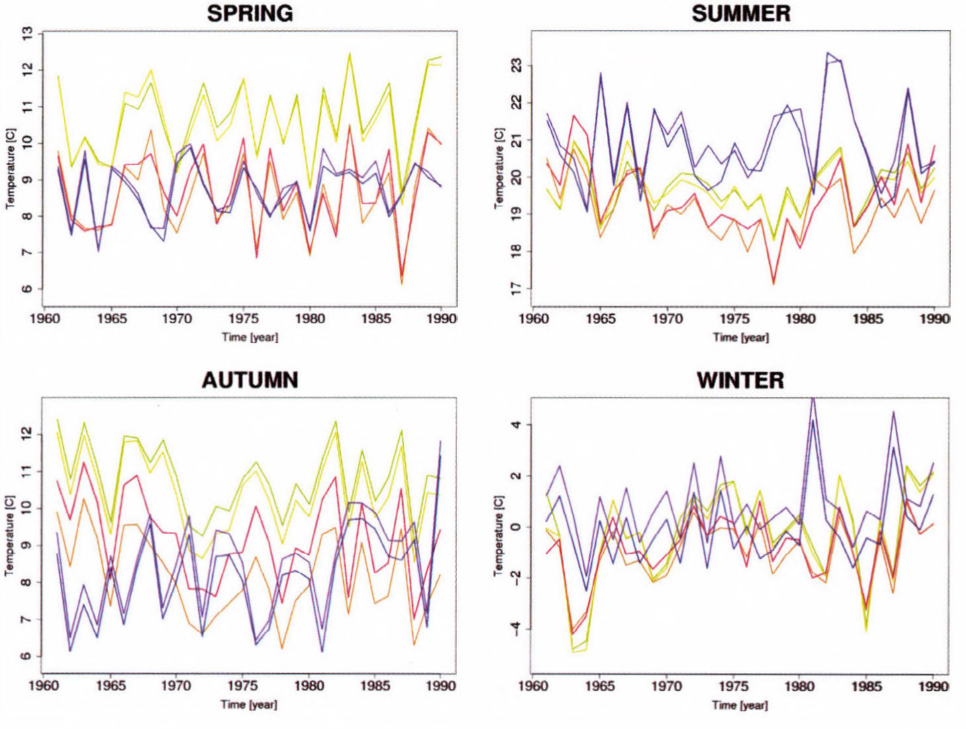

Fig. 6. Temporal evolution of the seasonal mean temperature of the examined models and observational data (CRU10: light green; HUGRID: yellow; ALADERA_25: red; ALADERA_10: orange; ALADARP: blue; ARPEGE: purple).

Correspondingly, studying the temporal evolution of the mean temperature during the 30 years examined (*Fig. 6*), the main variability features for the ERA-40-driven cases (red, orange) are naturally in good agreement with the observations (yellow and green). On the other hand, for the ARPEGE and ARPEGE-driven ALADIN-Climate (purple and blue, respectively) simulations of the variability characteristics can be evaluated only by considering the entire 30 years without any direct links to the individual years. This arises from the fact that only the global external forcing, and not the initial conditions, constrains the limited area model simulation; consequently the climate adaptation process is realized over a longer time scale.

For spring and autumn, all models underestimate the temperature in the entire period of 1961–1990. As the average distances between the different models and the observations are comparable, the models have roughly similar bias and RMSE values. On the other hand, while ARPEGE and ALADARP overestimate, the ERA-40-driven simulations underestimate the summer temperature throughout most of the years and, as in the transitional seasons, the model biases have essentially the same sign during the entire period. Therefore, smaller bias seems to indicate smaller RMSE (and vice versa) in all of the seasons except for winter. In the coldest season the ALADARP values are situated randomly under or over the observations, therefore, the systematic error is small in spite of the fact that the difference in errors between individual years can even exceed 5 °C, providing a large RMSE.

Summarizing the results for the temperature, it can be said that annually and in winter the systematic errors of the ARPEGE-driven ALADIN-Climate model seem to be lower than the reanalysis-driven models' errors. However, the results are comparable in the transitional seasons, and the ERA-40-driven versions have smaller biases than the other models in summer. As far as the RMSE and the year-by-year variability characteristics are concerned, the correlation between the ERA-40-driven cases and the observed data are obviously higher than is the case between the observations and ARPEGE or ALADARP. This fact corresponds to our initial expectations, indicating that the global model and the limited area model driven by the global one are unable to simulate the time series of annual or seasonal means. Subsequently, the frequency distributions are reasonably high and narrow in the cases of the ERA-40-driven simulations (low RMSE), and rather low and wide in the case of the ARPEGE and ALADARP ones (high RMSE).

4.2. Precipitation

From hereinafter only the ALADERA_25, ALADERA_10, and ALADARP simulations are evaluated.

Looking at the annual relative differences (the deviations between the simulations and the observations normalized by the corresponding values of the observational data), generally a 10–50% overestimation can be seen in the Carpathian Basin for all of the models investigated (*Fig. 7*). The systematic errors are much larger outside the basin, especially for the ALADERA_10 simulation. There is also an underestimation pattern appearing in the south-western part of the domain for every experiment, which is more pronounced within the high resolution model versions. The biggest errors are near to the model boundaries indicating spurious precipitation patterns originating from the lateral boundaries: it is especially true for the two 10 km integrations. Moreover, the lower resolution ALADIN-Climate model, due to the smaller biases at the edges of the visualization domain (which are not the physical boundaries in that case), has the smallest spatial variability in terms of model bias. The best simulation for the Carpathian Basin is the ARPEGE-driven one, which obviously indicates the importance of the proper dynamical and physical balance between the coupling and coupled models. The systematic error in the southwest part of Hungary is around zero, and basically, with some small exceptions, the errors remain under 30% throughout Hungary. A patchy picture can be seen in the results of ALADERA_25, which shows slightly worse results than ALADARP, but considerably better than the high resolution ERA-40-driven run. Although the largest systematic errors can be seen in the ALADERA_10 simulation, the errors are rather small in the southwest part of the Carpathian Basin. All of this means that the resolution increase for the ERA-40-driven models does not automatically improve the performance of the simulation. It might be attributed to the difference between the resolutions of the driving and the driven models. The increase in resolution is causing more discrepancy through the lateral boundaries and furthermore the proximity of the boundaries (which are situated over mountainous regions), which might cause unrealistic precipitation fields near to them.

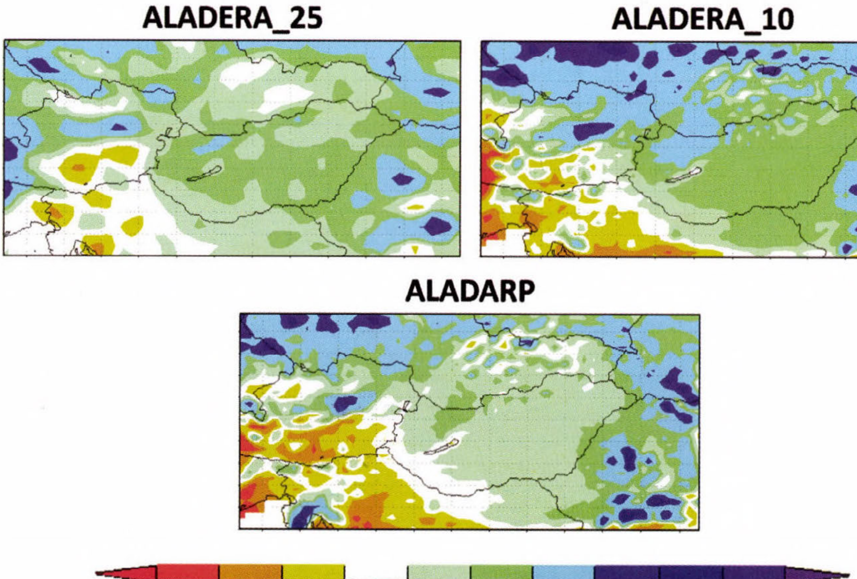

Fig. 7. Relative difference of annual mean precipitation for the period of 1961–1990 for ALADERA_25, ALADERA_10, and ALADARP (model simulation – CRU10)/CRU10 [%]).

Regarding the seasonal features in general, spring and summer are more humid than the observations in all of the simulations, and a relatively variable pattern with locally significant over- and underestimations can be seen during autumn and winter. While the relative difference of precipitation is around zero in winter in the Carpathian Basin, very extreme positive and negative values can be seen outside the basin, near the model boundaries. The autumn features are extremely different and the best results (as for the annual situation) are in the low resolution model case. The ALADERA_10 and ALADARP simulations are rather similar, except for summer, when the ARPEGE-driven integration performs significantly better than the ERA-40-driven one. It can also be seen that all of the models (even ALADERA_25) have very variable results outside the Carpathian Basin. Inside the Basin, all simulations give similar results in spring with a general significant overestimation pattern. This positive bias is also typical for the summer for all of the models. However, there is a significant difference between the worst version (ALADERA_10) and the best one (ALADARP). During the autumn very low bias (overestimation) can be seen in the Carpathian Basin in the 25 km resolution ERA-40-driven model. The other two models have larger negative systematic errors all across the domain. Regarding the winter season, while the ALADERA_25 results are rather similar to its autumn ones, the maps of the ALADERA_10 and ALADARP models have very different features. While the models underestimate the precipitation in the southwest and overestimate it along the other parts of the domain edges, the bias in the majority part of Hungary remains reasonably good. The biggest differences between the two model results are the (positive) extremes in the eastern part of the domain.

As far as the bias values are concerned, *Table 5* reflects the Hungarian situation as can be also derived from *Figs. 7* and *8*. These values help to quantify those small differences, which are otherwise difficult to interpret subjectively.

Table 5. Systematic errors of annual and seasonal simulated precipitation fields against the CRU10 and the HUGRID data in the case of ALADERA_25, ALADERA_10, and ALADARP experiments in the area of Hungary for the period of 1961–1990

Precipitation bias [mm/months]	**Annual**	**Spring**	**Summer**	**Autumn**	**Winter**
ALADERA_25 – CRU10	15.31	31.11	22.06	3.56	4.50
ALADERA_10 – CRU10	18.72	33.36	49.91	–8.53	0.14
ALADARP – CRU10	9.33	31.72	15.12	–10.20	0.83
ALADERA_25 – HUGRID	15.60	30.34	23.35	4.76	4.55
ALADERA_10 – HUGRID	18.69	32.14	50.96	–7.43	–0.26
ALADARP – HUGRID	9.30	30.49	16.17	–9.11	0.44

Taking into account the fact that the global models and the global model driven simulations are able to simulate only the long term inter-annual variability, as in the case of temperature, a short review of the results of the RMSE, the frequency distribution and temporal evolution charts of precipitation is given below.

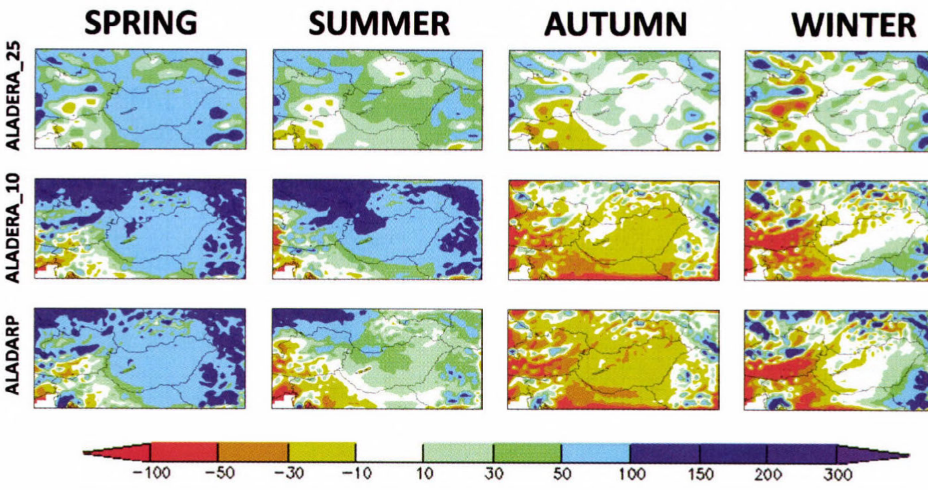

Fig. 8. Relative difference of seasonal mean precipitation for the period of 1961–1990 (model simulation – CRU10)/CRU10 [%]) (from top to the bottom: ALADERA_25, ALADERA_10, and ALADARP, respectively).

Table 6. Root mean square errors of annual and seasonal precipitation against the CRU10 and the HUGRID data in the case of ALADERA_25, ALADERA_10, and ALADARP experiments in the area of Hungary for the period of 1961–1990

Precipitation RMSE [mm/months]	**Annual**	**Spring**	**Summer**	**Autumn**	**Winter**
ALADERA_25 – CRU10	18.00	34.23	30.80	13.54	9.99
ALADERA_10 – CRU10	20.91	35.61	54.10	14.72	11.22
ALADARP – CRU10	15.58	37.12	35.58	22.09	18.25
ALADERA_25 – HUGRID	18.54	33.91	32.23	14.05	10.65
ALADERA_10 – HUGRID	21.19	34.68	55.57	14.81	12.78
ALADARP – HUGRID	16.39	36.36	37.04	22.75	19.89

As already explained and demonstrated for temperature, the small bias may not indicate small RMSE values due to the possible cancellation effects arising from the bias computations. In order to illustrate this feature for precipitation as well, the winter values of ALADARP and ALADERA_25 are considered. While the ALADARP experiment possesses a rather small bias value (0.83), the ALADERA_25 is characterized by a larger one (4.5). On the other hand the RMSE of ALADERA_25 is significantly lower (9.99) than in the case of ALADARP (18.25). Essentially, small bias corresponds to large RMSE (*Table 6*) and vice versa. That is because the ALADERA_25 integration has significant systematic overestimation – which is present for a large part of the domain in the majority of the years and in basically all the seasons –, but it does not manifest itself in big RMSE values because the overestimation values are not too big. In contrast, ALADARP results have very small systematic error, but significant RMSE values, at the same time, because there are significant errors of different signs across the domain and throughout the different seasons during the period studied.

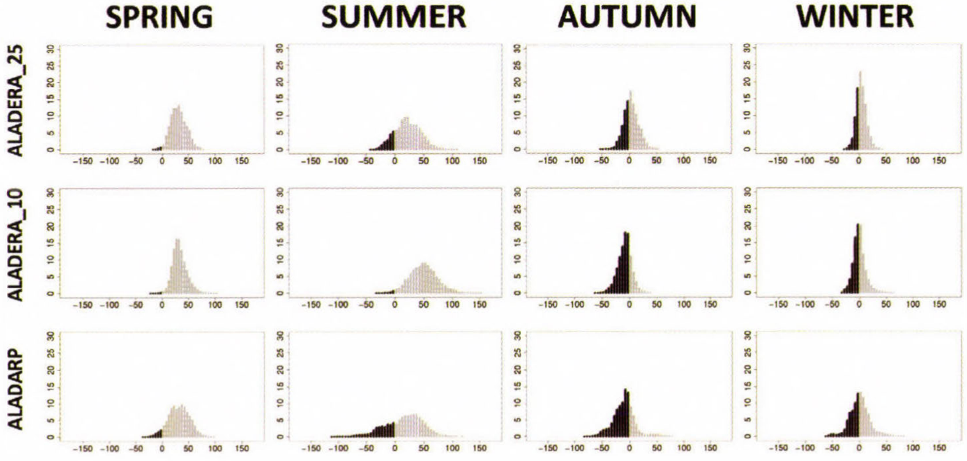

Fig. 9. The frequency distribution of seasonal precipitation differences with respect to CRU10 data for ALADERA_25, ALADERA_10 and ALADARP. X axis: difference of precipitation [mm] in the range of [–150, +150]. Y axis: frequency [%] in the range of [0, 30] (black: negative bias, gray: positive bias).

The same issue can be also seen, while looking at the frequency distribution of seasonal precipitation differences (*Fig. 9*). The two histograms for ALADERA_25 and ALADARP in winter are rather different: narrow, high, and asymmetric for ALADERA_25 and lower, wider, and more symmetric for ALADARP. There is an annual variation of the frequency distribution in every experiment; the histograms are relatively high and narrow in winter and low and wide in summer. This fact confirms that the general predictability of precipitation is much higher in winter than in summer. Although, the histogram of ALADARP is slightly lower and wider than the ALADERA_10's one in the warmest season, its RMSE remains smaller than that of the ALADERA_10. This is because the systematic errors of ALADARP are around zero and the errors are not extremely big, and in the case of ALADERA_10 the absolute errors are rather high and they are mostly realized in overestimations.

Regarding the seasonal mean precipitation variation (*Fig. 10*), it can be seen that, as expected, the two kinds of observations (CRU10 and HUGRID in green and yellow) run together. Also the trends of the ERA-40-driven cases (red, orange) are similar to the observational ones. Particularly, the maximum and minimum values are roughly at the same places, although the correlation, particularly during summer, is not as good as was the case for temperature. As ALADARP cannot represent the observed series of year (see Sect. 3), the behavior of the ALADARP simulation (blue) is rather different to the ERA-40-driven cases. During spring, all models overestimate the precipitation for every year of the period 1961–1990. For summer, the picture is more chaotic: the high resolution ERA-40-driven results are relatively far from the observations, while the lower resolution version is closer to reality. Nevertheless, the two curves are still basically parallel. In autumn the ERA-40-driven versions have some bias – the low resolution model overestimates and the high resolution one underestimates the precipitation. However, the differences are smaller than in spring and summer, hence the RMSE and bias values are lower. The correspondence between the different experiments and the observations is best during winter. This fact is also apparent on the rather high and narrow (i.e. small errors) distribution functions in that season (*Fig. 9*).

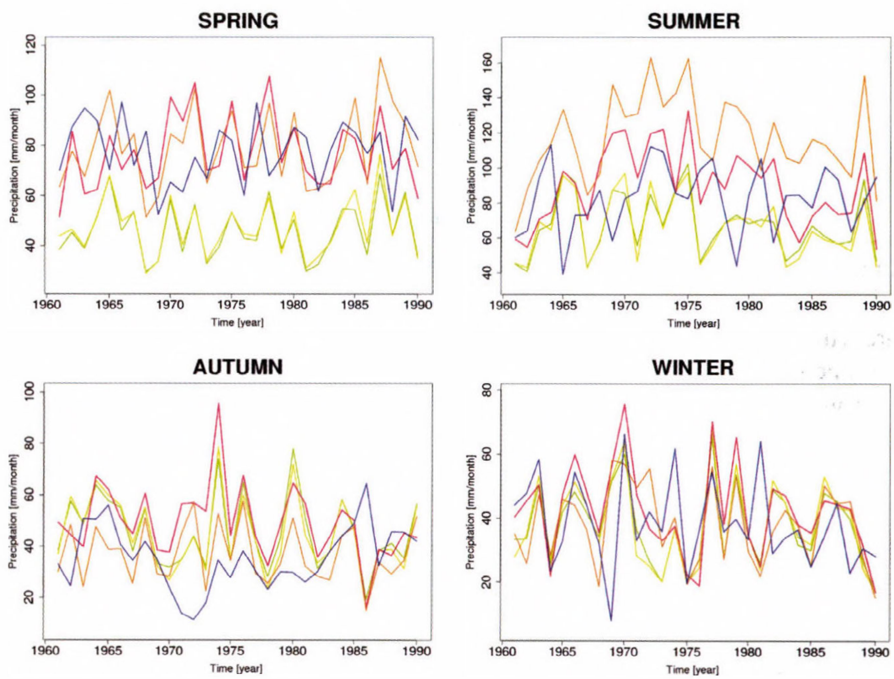

Fig. 10. The temporal evolution of the seasonal mean precipitation of the examined models and observational data (CRU10: light green; HUGRID: yellow; ALADERA_25: red; ALADERA_10: orange; ALADARP: blue).

In summary, the results of the simulated precipitation over the Carpathian Basin show that ALADARP is the best annually and in the extreme seasons. Regarding the RMSE and the inter-annual characteristics, the correlation between the ERA-40-driven cases and the observed data is unsurprisingly higher than is the case for the ARPEGE-driven simulation. On the other hand, the low resolution ERA-40-driven case (ALADERA_25) has better verification characteristics than that of the high resolution re-analysis-driven case (ALADERA_10).

5. Conclusions

The aim of this paper was to give a comprehensive analysis of temperature and precipitation fields of the ALADIN-Climate model "family" integrated at the Hungarian Meteorological Service. Four different kinds of simulation have been investigated in the case of temperature, and three in the case of precipitation. These simulations are the 25 km resolution ALADIN-Climate (LBC: ERA-40), the 10 km resolution ALADIN-Climate (LBC: ERA-40), the 10 km resolution ALADIN-Climate (LBC: ARPEGE-Climat) and, only in the case of temperature, the ARPEGE-Climat model. It was considered essential to explore the behavior of the available climate models for the recent past, since valuable information can be expected from the simulations of the future only if the main characteristics of the models are well known and its strengths and weaknesses are explored. This statement is true in spite of the well-known fact that the error characteristics for the past might not have any relation with those for the scenario runs. Moreover, it is also generally accepted that changes in the future are computed with respect to the same model simulations for the past. This technique implicitly assumes that the same error characteristics occur in the past as for the future (this fact cannot be verified and most probably is not true), hence the difference between the absolute fields automatically neglects those errors.

It was largely illustrated that the global climate models, and those regional climate models that are driven by global models, are not expected to simulate the time series of annual or seasonal means (only the long term inter-annual variability), since the global models do not provide any information on real years. Nevertheless, it is expected from all of the model versions that the average behavior of the atmosphere is reasonably well simulated for a longer time period (typically 30 years).

The figures and tables in this paper illustrated that the ARPEGE-driven version and even the driving model, in general, give better results in the Carpathian Basin for the whole period (1961–1990), than the ERA-40-driven versions. These results are certainly due to the much better physical and dynamical consistency between the ALADIN-Climate and ARPEGE-Climat models than between the limited area model and the ERA-40 data. Moreover, the coupled ALADARP gives better results than its mother model (the ARPEGE-Climat global model), providing the anticipated "added value" by the application of the higher resolution regional climate model.

The examination and comparison of the two "observation-driven" cases helps to draw some conclusions about the sensitivity of the simulations with respect to the domain size and resolution. The realization, that the lower resolution model (in a bigger domain) gives better results than the higher resolution one (in a smaller domain), points to the fact that the domain of the 10 km resolution model is too small, and the errors appearing at the edges of the model domain have a strong effect on the simulation of the inner area as well.

Finally, based on all of these results, we are tempted to conclude that the results of the ARPEGE-driven regional model – even in this small domain – might be used for making reasonably good projections for the future. If this "climate shift" or "climate transformation" of the investigated regional model is fairly comparable to other models known from different projects (e.g., ENSEMBLES (*ensembles-eu.metoffice.com*), PRUDENCE (*prudence.dmi.dk*), etc.) in low resolution, then this provides some reassurance that the model examined will probably provide reliable results and can be used in the future at higher resolution as well.

The future work will concentrate both on the issue of the optimal domain size and resolution for the Central-European climate simulations and on the scenario runs together with their evaluations for the determination of climate scenarios for the Hungarian territory.

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Analysis of heavy precipitation for France using high resolution ALADIN RCM simulations

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Abstract—A high resolution version of ALADIN over France is analyzed here in 30-year ERA-40-driven simulations. It is demonstrated that a resolution of 12 km improves some features of the mean precipitation field with respect to the same version at 50 km resolution. This version improves also the representation of precipitation upper quantiles in summer by producing less high precipitation rates.

Key-words: extreme events, precipitation, regional climate modeling, horizontal resolution, France

1. Introduction

Successful reproduction of large-scale features of climate, such as pole-to-equator gradient or location of main subtropical anticyclones from a set of equations, is a great challenge of numerical modeling. The average public, however, is little concerned. Similarly, predicting a global warming of 2 °C if carbon dioxide concentration doubles is little informative for the scientific impact community. The simulation of features at the scale of human activities, like the geographical distribution of precipitation over a country, is much more interesting for decision makers.

Regional climate modeling is thus an important issue. Climate simulation with a purely local model is not possible, except in idealized experiments, since the atmosphere has no borders. The first climate models were global or at least hemispheric (*Kasahara* and *Washington*, 1967; *Manabe et al.*, 1965). With increasing computer resources in the last decades, modelers have refined more and more the resolution of the general circulation models (GCMs). Increasing horizontal resolution corresponds to two categories of needs:

1) allowing a more accurate discretization of the Navier-Stokes equations which cannot be solved analytically; this also applies for vertical or time resolution: the higher the resolution, the closer the discretized solution to the exact solution,
2) enabling a better representation of surface forcing and, as a consequence, the meso- and synoptic scales.

In case 1) the minimum resolution seems to be 300 km, but further increases modify only to a limited extent the large-scale atmospheric circulation (*Sperber et al.*, 1994). This explains why during a quarter of century, GCMs have been run at that resolution. In case 2) there is no mesh size limit, since the scales of the forcing extend up to 1 km (mountain) and even to 1 mm (canopy).

Limited area climate models appeared some 25 years after the GCMs (*Giorgi*, 1990). An additional reason for the need of higher resolution in the 1990s was the availability of atmospheric reanalyses at typically 100 km resolution (ERA-40, *Uppala et al.*, 2005). Indeed, one can use regional climate models (RCMs) at high resolution as intelligent "interpolators" to produce data in area where observations are scarce or doubtful. Another recent and practical reason for higher horizontal resolution is the need by hydrologists for climate simulations taking into account surface elevation in the best possible agreement with their drainage basin. In a pioneer study, *Christensen et al.* (1998) showed that a LAM at high resolution (20 km) was able to produce intense local precipitation events which were not grid point storms.

The ALADIN model is a limited area version of the ARPEGE-IFS forecast system. It has been used in numerical weather prediction by a wide community since the 1990s (*Bubnova et al.*, 1995) and more recently in regional climate modeling (*Radu et al.*, 2008; *Farda et al.*, 2008). In the framework of the CECILIA European project presented in this special issue, ALADIN has been used at 10 km resolution over three domains, Czech Republic, Hungary, and Bulgaria. In the present study, we analyze a similar experiment with ALADIN covering a domain over France, with special emphasis on extreme precipitation. Although this study is not formally part of the CECILIA project, it has permitted to explore and extend the capacities of ALADIN to simulate climate at high resolution.

In this paper we want to investigate whether the ARPEGE-climate physical parameterizations, which has been developed for spatial scales between 50 km and 300 km, are still valid at higher resolution. In addition, we wish to verify if the increase in resolution can produce some details, which make the model closer to observation. We do not analyze the temperature field because:

- due to the small size of the integration domain, temperature is largely controlled by advection from the lateral boundary conditions,
- the small-scale details are easy to mimic by simple surface elevation correction (the maps of mean screen level temperature present strong similarities with the pattern of the orography map).

Simulating precipitation is a harder challenge, and the present paper will address this field, with a special attention to heavy daily precipitation.

The paper is organized as follows: in Section 2, we present the experiments and validation data. In Section 3, we validate seasonal mean precipitation. In Section 4, we examine the probability distribution function of daily precipitation, and we focus on its tail in Section 5. Then we conclude in Section 6.

2. *Experiments and data*

ALADIN is a limited area model issued from the ARPEGE-IFS software developed at Météo-France and ECMWF. Proper references have been given in the previous section. More specifically, here we use version 4.6 of the climate model which is based on cycle 24 of ARPEGE-IFS. Two model discretizations are used here: one with 50 km resolution, the other with 12 km resolution. The two integration domains have the same center, which is also the center of the Lambert projection (2°E, 47°N). The relaxation-free area is shown in *Fig. 1* (solid line for the 12 km resolution, dashed line for the 50 km resolution). The higher resolution domain is larger than the lower resolution one, because the relaxation zone is narrower (8 grid points on each side in both cases).

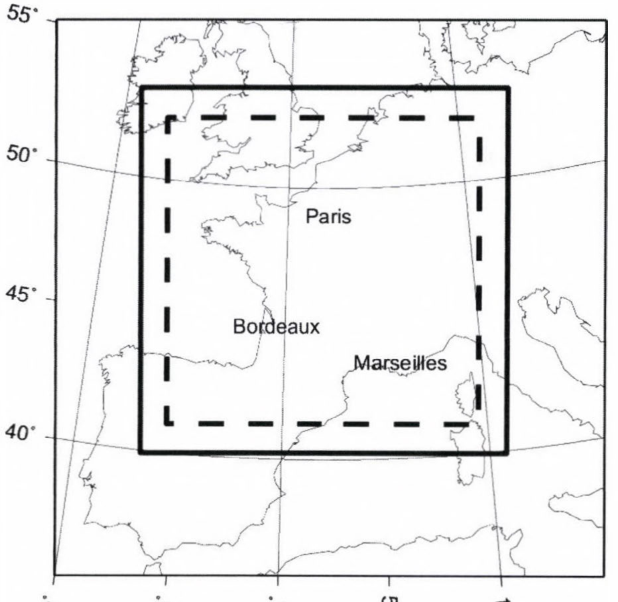

Fig. 1. Integration domain of the two ALADIN versions where no Davies relaxation is applied (i.e., without the 8 rows at each border): FR12 (solid) and FR50 (dashed).

The total number of grid points is 50 by 50 for the 50 km version, referred to as FR50 in the following and 150 by 150 for the 12 km version, referred to as FR12 in the following. There are 31 vertical levels in both cases, and the time step is 15 min for FR50 and 10 min for FR12. Except for mesh size and time step, the two versions have exactly the same physical parameterizations described in *Radu et al.* (2008).

A 41-year simulation has been carried out with each model (1960–2000). The 6-hourly lateral forcing is ERA-40 reanalysis (*Uppala et al.*, 2005). We examine here only 30 years (1971–2000) of both simulations. We have at disposal a high resolution (8 km grid) reanalysis over France since 1971 (*Quintana-Segui et al.*, 2008). Such a dataset, named SAFRAN, is essential to evaluate the added value of 12 km resolution versus 50 km resolution (*Déqué* and *Somot*, 2008). It has been obtained by optimal interpolation of all climatological stations over France, so the true resolution (distance between two actual observations) is rather 30 km on average. In a numerical model, the true resolution is also coarser than the mesh size, because of numerical diffusion. We have also used raw observations from three rain-gauge series to validate the SAFRAN series (see Section 4).

In order to make an easy comparison between three different resolutions, first we have selected the land grid points of FR50, which are located in the French metropolitan territory. Then, for FR12 and SAFRAN, each land grid point is associated to the nearest neighbor in the FR50 restricted grid. All FR50 grid points which have less than 12 neighbors in FR12 or less than 20 neighbors in SAFRAN are eliminated. Finally, we retain, for each FR50 remaining point 12 neighbors for FR12 and 20 neighbors with SAFRAN. We have thus 166 boxes containing each 1 point of FR50 grid, 12 points of FR12 grid, and 20 points of SAFRAN grid. These numbers of 12 and 20 are a trade-off to keep the maximum number of boxes with the maximum of points inside: if we had imposed more points in the boxes, we would have got less boxes. This selection avoids sampling artifacts in coastal or border regions by ensuring equi-populated boxes. Indeed, the variance of box-averages decreases with the size of the box, and we could get higher extremes with small-populated boxes.

3. Seasonal mean precipitation

Let us first consider 30-year averages for each season. *Fig. 2* shows the precipitation distribution over France in summer (JJA) for SAFRAN, FR50, and FR12. The model is too wet, but reproduces the main geographical contrasts, and increasing resolution does not increase precipitation (a feature often observed in ARPEGE GCM). The model precipitation rates are too large over high mountains (Alps and Pyrenees). One can see that the pattern of Massif Central precipitation (just south to the center of France) is improved by higher resolution (unrealistic double maximum in FR50).

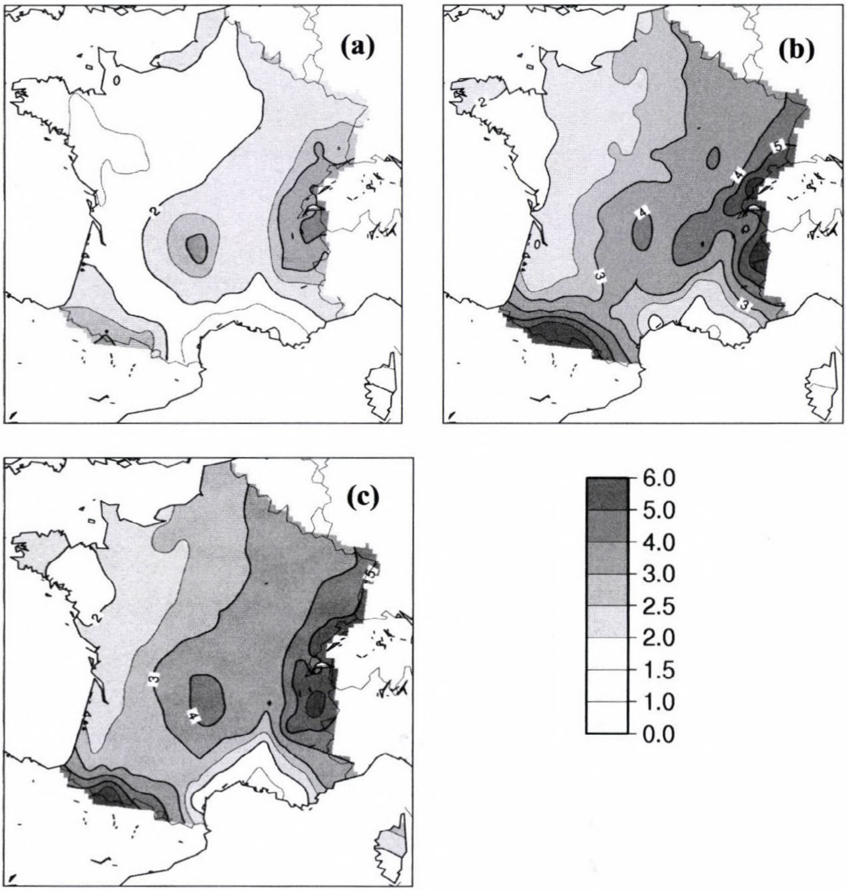

Fig. 2. Mean summer precipitation for SAFRAN (a), FR50 (b) and FR12 (c). Contours: 1, 1.5, 2, 2.5, 3, 4, 5 and 6 mm/day.

To make the comparison more accurate, precipitation is averaged in each box (see previous section for definition of the 166 boxes), and root mean square error (RMSE) is calculated for each season with respect to SAFRAN. *Table 1* shows the results. In each season, the higher resolution is superior to the lower one. The improvement is not spectacular, but systematic.

Table 1. Root mean square error of precipitation (mm/day) over France for seasonal means with the two ALADINs versions calculated on 50 km × 50 km averages.

	DJF	**MAM**	**JJA**	**SON**
FR50	0.72	1.37	1.32	0.76
FR12	0.65	1.24	1.16	0.59

4. Precipitation probability density functions

In order to evaluate the precipitation probability density function (pdf), quantile-quantile (q-q) diagrams of ALADIN and SAFRAN versus observation are plotted for three French cities. Paris is representative of the climate of the northern half of France. In the southern half, due to the presence of Massif Central mountains and Mediterranean sea, two climates are observed: Bordeaux is representative of the oceanic climate, whereas Marseilles is representative of the Mediterranean climate. In fact, Bordeaux and Paris climates are not so different, but there is a latitudinal and continental gradient at a time between the two cities. The location of the three cities is indicated in *Fig. 1*.

We consider here daily precipitation over 30 years. Each calendar season is analyzed separately. The quantile resolution is 1/1000 (probabilities between 0.1 and 99.9%). Three methods have been used to evaluate the quantiles in the boxes.

- Method 1 consists of averaging precipitation in each of the 3 boxes closest to the 3 cities, as we did in last section for RMSE over whole France. This method favors the extremes in FR50, because no spatial averaging is performed before sorting daily precipitation.
- Method 2 consists of computing quantiles for each model grid point, whatever the resolution. Then the quantiles are averaged for all grid points of a given box. This allows a fairer comparison between two resolutions, because no preliminary damping of high resolution data is applied before sorting.
- Method 3 consists of sorting the daily precipitation data of all points inside a box (pooling). This allows a better sampling of higher quantiles in high resolution data.

For FR50, the three methods are identical, because there is only one grid point per box. This is also the case with observations: we have a single time series for each city. In order to better capture the differences between the three methods, let us use the following notations:

R_{ijk} is precipitation for box i (i = 1,3 for the closest box to Paris, Bordeaux, and Marseilles), grid point j (j = 1,20 for SAFRAN grid, j = 1,12 for FR12 grid, and j = 1 for FRA50 grid), and day k (k takes about 2700 values depending on the season). A^x means averaging for index x ($x = j$ or k) and S^x means sorting with respect to index x.

- Method 1 computes $S^k(Aj(R_{ijk}))$.
- Method 2 computes $A^j(Sk(R_{ijk}))$.
- Method 3 computes $S^{jk}(R_{ijk})$.

From statistical point of view, methods 2 and 3 evaluate the same quantity, provided that each box is homogeneous. Method 3 is more accurate, in particular for extreme values, whereas Method 2 allows to calculate a confidence interval with some hypotheses. For our three cities, Methods 2 and 3 give similar results, whereas Method 1 provides systematically less precipitation rates, because of spacial averaging of wet and dry grid points.

Fig. 3 shows the q-q plots for DJF and JJA obtained by Method 3. For the three locations, SAFRAN provides a pdf in good agreement with raw station data (except for Paris JJA beyond 99% quantile). This indicates that the SAFRAN interpolation algorithm is not detrimental to high precipitation events. FR12 provides systematically less precipitation than FR50, whatever the quantile. Both models are generally below the diagonal of the diagram, indicating less precipitation than observed, except for summer precipitation below 5 mm/day, where both models exaggerate the quantities.

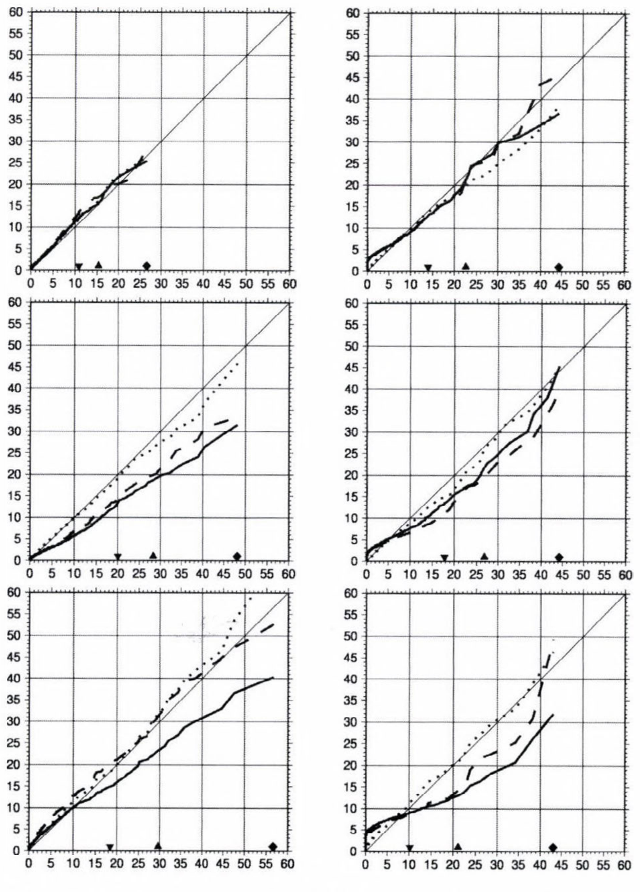

Fig. 3. Quantile-quantile plots of winter (left) and summer (right) daily precipitation (mm/day). Observed quantiles are sorted along the x-axis and model/analysis quantiles are sorted along the y-axis. Solid line corresponds to FR12, dashed line to FR50, and dotted line to SAFRAN. Top panels correspond to Paris, medium panels to Bordeaux, and bottom panels to Marseilles. The 99.9%, 99%, and 97.5% observed quantiles are indicated along the x-axis by a diamond, a triangle, and an inverted triangle, respectively.

From this first analysis, it appears that we can rely upon SAFRAN data for precipitation pdf, that FR12 and FR50 behave similarly for Paris and Bordeaux, but FR12 is worse than FR50 for Marseilles.

5. *Heavy precipitation events*

In order to make a more systematic comparison over France without inflating the paper with maps, we must use a quality criterion. The ranked probability score (*RPS*, *Epstein*, 1969) is well adapted to pdf comparison for variables like precipitation. It is widely used in probability forecast evaluation. It is simply based on the euclidean distance between the cumulated density functions (cdf) for a set of thresholds t_i, $i = 1, n$:

$$RPS = \sum_{i=1}^{n} \left[\mathrm{Prob}(MOD < t_i) - \mathrm{Prob}(REF < t_i)\right]^2 , \tag{1}$$

where *MOD* is FR12 or FR50 daily precipitation and *REF* is SAFRAN precipitation. Generally, the thresholds t_i are chosen to sample the pdf in a homogeneous way by taking the quantiles of a climatological distribution. Here we want to measure the fit of the tail of the distribution, so we selected the quantiles above 95% from the SAFRAN pdf ($n = 49$). The *RPS* is a dimensionless quantity and can be averaged for France, as the *MSE* in Section 3. However, a squared difference between two quantities close to each other (order of magnitude 0.95–1.00 each) produces small values, and we multiplied this score by 10^4 to handle quantities with order of magnitude 1. With this scaling, an *RPS* of 1 corresponds to a departure of 0.01 (e.g., 98% versus 99%) between ALADIN and SAFRAN cdf. *Table 2* shows *RPS* for each season. The 3 aggregation methods have been used to calculate the pdf. Methods 2 and 3 give similar *RPS*, which are smaller than those of Method 1. However, the conclusion is the same, whatever the method: FR12 has a better pdf tail than FR50, except in winter.

Table 2. Ranked probability scores for the tail of precipitation pdf (dimensionless units multiplied by 10^4) over France per season and with the 3 aggregation methods

	Method 1		**Method 2**		**Method 3**	
	FR50	**FR12**	**FR50**	**FR12**	**FR50**	**FR12**
DJF	1.88	2.50	1.65	2.34	1.56	2.16
MAM	3.15	1.44	2.18	1.13	2.04	1.16
JJA	1.73	0.66	1.39	0.64	1.35	0.66
SON	1.37	1.06	1.22	1.03	1.20	1.00

Fig. 4 helps to localize the weaknesses of the model pdf. It shows the ratio of the 99.9% quantiles between ALADIN and SAFRAN. The return period corresponding to this quantile is about 10 years, because one year contains about 90 days per season, so 10 years corresponds to 1000 values and thus to a probability of 0.1%. In winter, the behaviors of FR12 and FR50 are similar: the model overestimates the return value in the center of the country and underestimates it in the rest of the country. Contrary to the RPS results (which take into account all quantiles between 95% and 99.9%), there is no evidence that FR12 is worse than FR50. In particular, the underestimation by 30% in the southeast is improved by increasing resolution. In summer, the superiority of FR12 is obvious. FR50 produces return values in excess by 50% with respect to SAFRAN in some part of the country. However, FR12 is still too weak in the Mediterranean region.

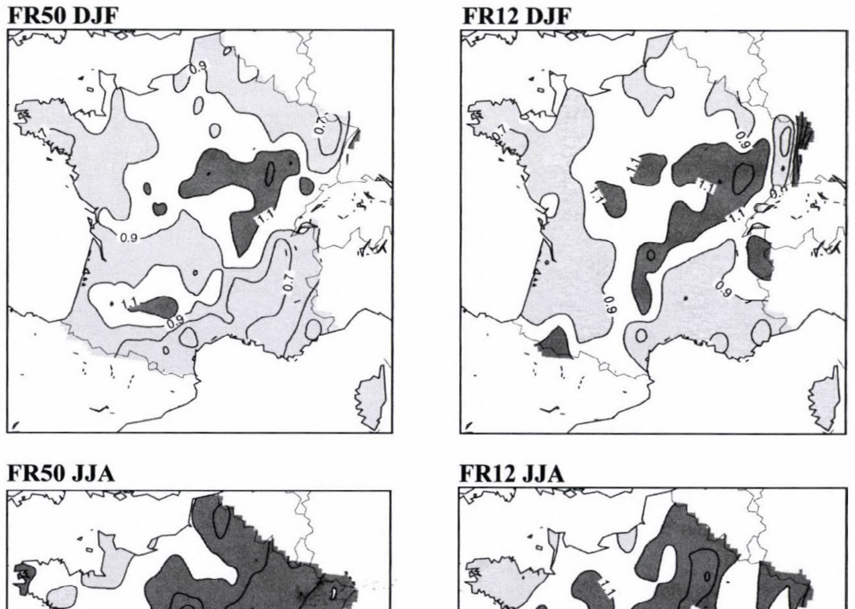

Fig. 4. Ratio of the 99.9% quantiles FRA50 over SAFRAN (left) and FRA12 over SAFRAN (right) in winter (top) and summer (bottom). The contour interval is 0.2, values over 1.1 are dense shaded, and values below 0.9 are light shaded.

We also computed the absolute maximum of precipitation of individual grid points by pooling all seasons (not shown). This 30-year maximum is about 50 mm/day over most of France for SAFRAN and ALADIN, but in the Cevennes region (southeast), it reaches 260, 144, and 108 mm/day for SAFRAN, FR12 and FR50, respectively. The highest events occur in autumn. The accurate representation of this kind of event is out of scope of ALADIN-climate.

6. Conclusion

The above results show that ALADIN is able to simulate the seasonal mean precipitation field and the tail of the probability distribution function (from one month to ten years return periods). For most quality criteria, the 12 km resolution version of ALADIN is superior to the 50 km one. The relatively small size of the domain (about 1200 km for the relaxation-free area) is not too detrimental to the simulation over the country, since no spurious strong precipitation stripes have been found over France. However, this small size does not allow the RCM to produce its own climate: we are here in a typical numerical downscaling exercise.

In the validation process of extreme precipitations, we used an alternative strategy by not considering a model grid point as a spatial average of observations, but by considering that a sample of grid points represents statistically a sample of observations. SAFRAN data are not really a series of observations, but the result of optimal interpolations. Using raw rain-gauge data over France is more complex, because the density is one observation per 10 km in some areas and one observation per 100 km in other areas. In *Déqué* (2007), such a comparison is performed with a 50 km resolution RCM.

Two important points are not addressed in this study. The first one is the space and time distributions of the highest precipitation extremes. As shown in previous section, the distribution is not uniform over France and the highest events are observed in the southeastern part in Autumn. The ALADIN-climate model, which is based on hydrostatic equations (in our climate version) with a full parameterization of convection, is not able to reproduce them quantitatively. To our knowledge, only 2-1 km resolution non-hydrostatic models like Meso-NH (*Ducrocq et al.*, 2008) can produce them explicitly. However, a recent study performed in the French project CYPRIM suggests that coarser resolution models like ARPEGE or ALADIN can produce strong rainy events (with respect to model quantiles) at a reasonable frequency. When the non-hydrostatic model Meso-NH is driven by ARPEGE during these events, it produces large amounts of rainfall (above 200 mm/day). This shows that one can use ARPEGE or ALADIN precipitation as a proxy of severe events with a proper statistical postprocessing (*Déqué*, 2007).

The second point is the added value of high resolution. The fact, that the probability distribution is improved in FR12, is not a proof that the spatial distribution of the 12–50 km scale structures is improved. In *Déqué* and *Somot* (2008) we show, that the spatial correlation of FR12 versus SAFRAN inside each 50 km box is significantly better than the correlation of FR50 interpolated onto the FR12 grid.

The perspective of this study is to extend the extreme precipitation analysis to CECILIA domains (Czech Republic, Hungary, Bulgaria, and Romania), where high resolution daily precipitation observations will be available soon. We plan to run the same scenarios (IPCC-A1B 2021–2050 and 2071–2100) with FR12 as in CECILIA. PRUDENCE simulations (*Christensen* and *Christensen*, 2007) at 50 km resolution suggest that the upper quantiles should increase in a warmer climate. As we have illustrated here that 12 km resolution ALADIN has a generally better representation of precipitation extremes than FR50, it is worth checking that the upper quantiles increase as a response of global warming is still valid at 12 km resolution.

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Validation of ALADIN-Climate/CZ for present climate (1961–1990) over the Czech Republic

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Abstract—Two present-time climate simulations performed with a regional climate model ALADIN-Climate/CZ in the framework of the EU FP6 project CECILIA were investigated to assess the model's ability to reproduce the main patterns of 2-meter temperature and precipitation in the orographically complicated region of Central Europe. To allow a direct comparison of high-resolution model outputs with the station data over the territory of the Czech Republic, a new gridded dataset with the same 10 km resolution was created. The obtained results of the first evaluation dealing with the model's performance during the control period 1961–1990 are presented here. In term of mean values, the model driven by the ERA-40 re-analyses is in better accordance with the observed data than when it is forced by the global circulation model ARPEGE-Climat. The selected characteristics based on daily maximum and minimum temperatures and sum of precipitation are very similar in both simulations. Although the evaluation has revealed weaknesses originating either from the model itself or driving data, the overall performance of the model is reasonably good in both simulations.

Key-words: regional climate modeling, validation, temperature, precipitation, gridding, ALADIN, Czech Republic

1. Introduction

Regional climate models (RCMs) are the state-of-the-art tools employed for downscaling information from the coarse resolution global circulation models (GCMs) on a local scale. With their increasing popularity for climate change

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studies, it is important to assess the reliability of the information provided by RCMs. Validation of RCMs outputs is based on their comparison with a reference dataset, e.g., re-analysis fields or observed data. It is made much easier when the observed data is available on the same regular grid as the model. Real station observations are irregularly spatially distributed and, therefore, first they must be interpolated into a regular grid. There are already several existing gridded datasets of observations. Many of them have got either shorter time span or cover only a limited region, however. Those ones covering major parts of Europe and having the records at least for the period 1961–2000 are rather at coarse spatial resolution (~50 km). The best currently available European gridded dataset was prepared as a part of the ENSEMBLES project, and it contains high resolution (~25 km) daily data for precipitation and minimum, maximum, and mean temperatures for the period 1950–2006 (*Haylock et al.*, 2008).

The Czech Hydrometeorological Institute (CHMI) is a member of the international consortium developing and using the limited area model ALADIN for weather prediction. At the beginning of the 2000s the tests showed the model's capability to be run for a longer period and adapted for climate research purposes (*Huth et al.*, 2004). The further work has led to development of a regional climate model that is now designated as ALADIN-Climate/CZ. Unlike many other contemporary RCMs, ALADIN-Climate/CZ is a spectral model based on a semi-implicit semi-Lagrangian scheme as described in *Temperton* and *Staniforth* (1987). Physical computations are performed in the conventional grid space, however. The set of parameterizations is briefly described below. The model uses a convection scheme designed according to *Bougeault* (1985), a simple diagnostic cloudiness scheme together with large-scale precipitation parameterization (including evaporation of droplets), and the newly improved version of ACRANEB radiation scheme described in *Ritter* and *Geleyn* (1992). More detailed description of the model and its set of physical parameterizations can be found, e.g., in *Gerard* (2001) or *Farda* (2008). We would like to stress here that ALADIN-Climate/CZ is a different model than the RCM ALADIN-Climat developed at the Centre National de Recherches Météorologiques (CNRM) of Météo-France and employed also in other countries of the ALADIN consortium (*Spiridonov et al.*, 2005). Although both models share the same dynamical core and basic principles and formulations, they differ significantly in their physical parameterization packages. Physical parameterizations of the CNRM's ALADIN-Climat model are derived directly from those used in GCM ARPEGE-Climat 4 (*Déqué*, 2007), while those of the CHMI's ALADIN-Climate/CZ arises from parameterizations in the ALADIN numerical weather prediction version CY28T3 that was in operational use at CHMI in the years 2003 and 2004.

2. *Experiment setups*

Two simulations of present climate conditions were performed with ALADIN-Climate/CZ over the Central European domain in resolution of 10 km. These runs used either perfect lateral boundary conditions (LBCs) represented by the ECMWF ERA-40 re-analyses (*Uppala et al.*, 2005) or LBCs coming from a driving model planned to be taken for scenario runs (GCM ARPEGE-Climat in our case). While forcing by the GCM ARPEGE-Climat could be done directly due to the ARPEGE-Climat's high horizontal resolution (~50 km over Central Europe), a double nesting technique was applied to enable RCM ALADIN with 10 km grid to be driven by the ERA-40 re-analyses with coarse resolution. The ALADIN 50 km grid integration forced by the ERA-40 re-analyses (originally coming from the EC FP6 ENSEMBLES project) was taken to drive the model at 10 km resolution over the smaller Central European domain. The sea surface temperature fields came either directly from the ERA-40 re-analyses (ERA-40 experiment) or from the atmosphere-ocean GCM ARPEGE/OPA data (ARPEGE-Climat experiment). A brief summary of both experiments' setups is in *Table 1*. The whole integration domain and illustration of the model's orography are presented in *Fig. 1*.

Table 1. Model setup for the experiments

Experiment designation	ERA-40	ARPEGE-Climat
Integration domain size (lat. × lon.)	74 × 148 points	
Horizontal resolution	10 km	
Vertical resolution	43 levels	
Time step	450 s	
Integration period	Jan 1, 1960 – Dec 31, 2000	Jan 1, 1960 – Dec 31, 2000
Input data	ERA-40 re-analyses*	GCM ARPEGE-Climat

* by nesting through the ALADIN 50 km resolution integration

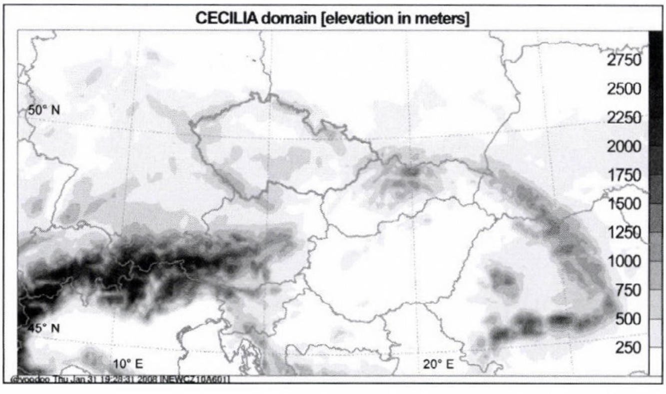

Fig. 1. Orography over the Central European model's integration domain.

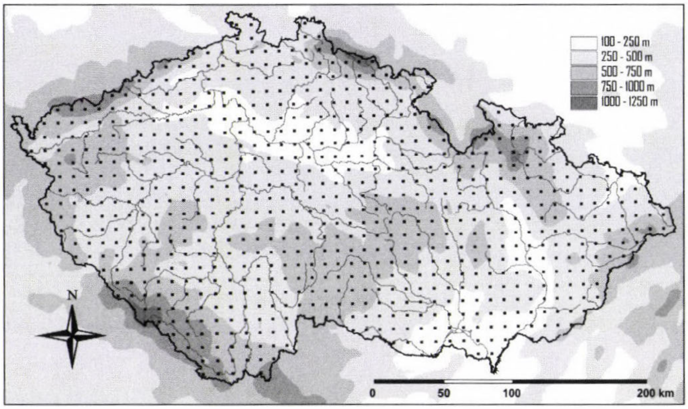

Fig. 2. Grid points and orography of the model in the Czech Republic. Elevation is in meters.

3. *Data and methodology*

For validation of the model results against the station data over the territory of the Czech Republic, a new gridded dataset of comparable spatial, 10 km resolution was created. It is based on the records stored in the CHMI climatological database. The daily data of four meteorological parameters (precipitation, mean, maximum, and minimum temperatures) from 302 stations measuring 2-meter temperature and 787 stations measuring precipitation were taken and recalculated to the model's grid (*Fig. 2*). The station data were at first reduced to the altitude of a selected grid point by applying a local linear regression and then the reduced values were interpolated to a position of the grid point. The inverse distance weighting was selected as the interpolation method. The weight parameter was set as $1/d$ in case of temperature and $1/d^3$ for precipitation, where the variable stands for d distance. In addition, when interpolating, a trimmed mean was applied for the temperature characteristics, thus excluding the values smaller than the 20th percentile and larger than the 80th percentile from the data of the input of every interpolation step. The gridding as well as quality control and homogenization of the input station data were done by the ProClimDB application (*Štěpánek*, 2008).

4. *Results*

Some of our very preliminary results obtained by a comparison of the model outputs to the newly created gridded dataset of station observations are presented here. We focused only on the territory of the Czech Republic. The reference period used for this study is 1961–1990.

Table 2 shows the basic statistics of the biases between model and station data. Long-term seasonal means of 2-meter temperature and sums of precipitation (expressed in millimeters per day) are included for both experiments. A column containing mean values refers to an average regional bias calculated from 789 grid points over the Czech Republic, while maximum and minimum values represent an extreme bias belonging to one particular grid point of the total.

Table 2. Regional average and extremes of seasonal biases (model versus gridded station dataset) of 2-meter temperature and precipitation fields over the Czech Republic in the period 1961–1990. The model experiments are designated according their LBCs. (DJF = winter, MAM = spring, JJA = summer, and SON = autumn)

Season	**Dataset**	**2-meter temperature (°C)**			**Precipitation (mm/day)**		
		minimum	**mean**	**maximum**	**minimum**	**mean**	**maximum**
DJF	ERA-40	–1.8	0.1	1.4	–2.6	0.2	4.1
	ARPEGE	–1.8	0.5	1.8	–1.8	0.7	5.7
MAM	ERA-40	–2.4	–0.9	0.5	–1.3	0.3	3.8
	ARPEGE	–2.8	–1.2	0.1	–0.6	0.9	5.3
JJA	ERA-40	–1.5	0.2	1.9	–0.6	0.6	3.2
	ARPEGE	–0.5	0.9	2.6	–0.7	0.7	3.2
SON	ERA-40	–1.3	0.4	1.9	–1.9	0.0	2.8
	ARPEGE	–2.8	–1.1	0.3	–1.6	0.2	4.1

In term of mean values, the model driven by ERA-40 captures well the 2-meter temperature in winter, summer, and autumn with positive biases less than 0.5 °C. In spring it exhibits a more pronounced cold bias (–0.9 °C), however. The latter can be also detected when GCM ARPEGE-Climat is used as a source of the driving data. The ARPEGE-Climat experiment also exhibits another significant cold bias in autumn (–1.1 °C) which is not corresponding to the warm bias (+0.4 °C) in the ERA-40 experiment. The positive biases, larger than those in the ERA-40 experiment, dominate in the ARPEGE-Climat experiment in winter and summer. The range of the seasonal biases among the grid points on the territory of the Czech Republic is similar in both experiments in all seasons. The high individual seasonal biases, whose extreme values are listed in *Table 2*, are mainly due to the remaining differences between the real and model orography.

Precipitation is corresponding well to the station data in autumn, otherwise in other seasons the model is more humid in both experiments than stations. The highest seasonal bias in the ERA-40 experiment is detected in summer (+0.6 mm/day), while in the ARPEGE-Climat experiment it is in spring (+0.9 mm/day). The seasonal biases in the ERA-40 experiment are always smaller than in the ARPEGE-Climat experiment. The range of the seasonal biases among the grid points on the territory of the Czech Republic is a little larger when the model is driven by the GCM ARPEGE-Climat.

In *Table 3* percentiles of daily mean temperature for each of 12 months in the year are presented. These were calculated as an spatial average from the percentile values computed in the grid points within the studied area. The percentile in a single grid point was derived from the series of daily mean temperatures over the whole period 1961–1990 for each particular month.

Table 3. Percentiles of 2-meter temperature derived from the daily data in individual months in the period 1961–1990 and averaged over the Czech Republic in the model experiments (designated according their LBCs), compared with the gridded station dataset

Percen-tile	Dataset	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1st	ERA-40	-11.7	-9.2	-6.8	-0.4	3.9	8.6	11.3	10.4	7.0	1.2	-5.2	-9.1
1st	ARPEGE	-12.9	-9.5	-5.9	-3.4	4.2	9.3	11.8	12.6	5.8	-4.1	-7.8	-11.2
1st	Stations	-17.4	-13.7	-9.6	-0.9	3.2	7.5	10.1	9.5	5.4	-0.2	-7.4	-13.8
5th	ERA-40	-8.6	-7.0	-4.1	0.8	6.3	10.2	12.4	11.9	8.6	2.8	-3.2	-6.9
5th	ARPEGE	-10.3	-6.9	-3.5	-1.0	5.8	10.9	13.1	13.9	7.2	-0.8	-5.3	-7.7
5th	Stations	-12.6	-9.5	-5.1	1.0	5.8	9.4	11.4	10.9	7.2	1.8	-4.1	-9.7
25th	ERA-40	-4.2	-3.3	-0.4	3.5	9.5	12.9	15.1	14.4	11.4	6.1	0.0	-3.4
25th	ARPEGE	-5.7	-2.0	-0.2	2.4	8.7	13.7	15.2	16.1	10.2	2.8	-1.7	-3.0
25th	Stations	-5.7	-3.9	-0.3	4.1	9.4	12.5	14.1	13.7	10.2	5.2	0.1	-3.7
50th	ERA-40	-2.0	-1.0	1.5	5.5	12.0	15.0	17.2	16.5	13.5	8.5	2.3	-1.3
50th	ARPEGE	-2.6	0.6	1.9	4.8	11.2	16.1	17.0	17.8	12.8	5.8	1.1	-0.6
50th	Stations	-1.9	-0.5	2.5	6.9	12.1	15.3	16.6	16.1	12.6	7.9	2.6	-0.7
75th	ERA-40	0.0	0.8	3.4	7.8	14.3	17.2	19.2	18.7	15.7	10.8	4.8	0.9
75th	ARPEGE	-0.4	2.7	4.0	7.1	14.0	18.2	18.8	19.5	15.1	8.7	4.2	1.7
75th	Stations	0.7	1.7	5.3	9.9	14.9	17.9	19.3	18.6	15.1	10.6	5.3	1.8
95th	ERA-40	2.9	3.2	6.3	11.4	17.5	19.8	21.8	21.5	18.5	14.0	8.4	4.2
95th	ARPEGE	2.3	5.7	7.0	10.2	17.4	20.8	21.6	22.2	18.9	12.6	8.1	5.2
95th	Stations	4.1	5.1	9.6	14.1	18.3	21.4	22.4	22.0	18.4	14.1	9.2	6.3
99th	ERA-40	4.7	5.1	8.1	13.6	18.9	21.1	23.6	23.1	20.3	15.8	10.8	6.8
99th	ARPEGE	4.2	7.9	8.8	12.2	19.0	22.7	23.6	24.1	21.9	15.5	10.5	7.5
99th	Stations	6.3	7.8	12.2	17.0	20.6	23.2	24.3	24.0	20.6	16.1	11.5	8.7

The p-% percentiles of 2-meter temperature for $p = 1$ and $p = 5$ ($p = 95$ and $p = 99$) are smaller (larger) in the gridded station dataset than in the model experiments in most cases. A certain exception from above can be found in the ARPEGE-Climat experiment in April, October, and November, when the 1st and 5th percentiles are smaller than in the gridded station dataset, in April and October even significantly (more than 2 °C). Similar exception can be detected in the ARPEGE-Climat experiment in February, August, and September when the 90th and 95th percentiles are larger in the model than station observations, although the differences are rather small (on about several tenths of °C). The mean values of the 2-meter temperature distribution (between the 25th and 75th percentiles) in the ERA-40 experiment are usually closer to those in the gridded station dataset except for March, September, and December when the ARPEGE-Climat experiment is in better accordance. The ARPEGE-Climat experiment also captures the lower end of the 2-meter temperature distribution (represented here by the 1st and 5th percentiles) better in winter and September. For higher end of the 2-meter temperature distribution (represented here by the 95th and 99th percentiles), the ARPEGE-Climat shows better accordance than the ERA-40 experiment approximately in half of the cases.

Tables 4 and *5* present the long-term spatial means in the occurrence of days with daily maximum (TMA) or minimum (TMI) air temperature and sum of precipitation (PR) over (or under) a defined threshold.

Table 4. Long-term (1961–1990) average of seasonal and annual numbers of tropical (TMA ≥ 30 °C), warm (TMA ≥ 25 °C), ice (TMA < 0 °C), arctic (TMA ≤ –10 °C) and frost (TMI < 0 °C) days averaged over the Czech Republic in the model experiments (designated according their LBCs), compared with the gridded station dataset. (DJF = winter, MAM = spring, JJA = summer, and SON = autumn)

Season	**Dataset**	**Number of days (TMA and TMI in °C)**				
		TMA ≥ 30	**TMA ≥ 25**	**TMA < 0**	**TMA ≤ –10**	**TMI < 0**
DJF	ERA-40	0.0	0.0	30.6	0.2	80.9
	ARPEGE	0.0	0.0	29.7	0.6	75.8
	Stations	0.0	0.0	33.2	1.2	73.3
MAM	ERA-40	0.0	0.2	2.3	0.0	39.7
	ARPEGE	0.1	0.3	2.1	0.0	40.0
	Stations	0.1	2.5	2.8	0.0	28.8
JJA	ERA-40	1.2	12.2	0.0	0.0	0.0
	ARPEGE	1.4	13.5	0.0	0.0	0.0
	Stations	4.2	26.5	0.0	0.0	0.1
SON	ERA-40	0.1	2.3	1.6	0.0	19.9
	ARPEGE	0.3	1.9	4.6	0.0	28.6
	Stations	0.2	2.7	2.8	0.0	20.9
YEAR	ERA-40	1.4	14.7	34.5	0.2	140.4
	ARPEGE	1.7	15.7	36.4	0.6	144.5
	Stations	4.4	31.7	38.9	1.2	123.0

In winter the numbers of ice (TMA < 0 °C) and frost (TMI < 0 °C) days are well corresponding to the observed data in both experiments, but the occurrence of arctic (TMA ≤ –10 °C) days is slightly underestimated. In spring the number of frost days is overestimated in both experiments, while the warm events characterized by the number of warm (TMA ≥ 25 °C) days are underestimated. The latter is also valid for the occurrence of warm events in summer. In autumn the number of warm days is slightly lower in both experiments than in the observed data. The cold events are represented well in the ERA-40 experiment in autumn, but they are overestimated in the ARPEGE-Climat experiment, especially considering frost days. In term of annual numbers, good agreement between the experiments and observed data occurs only in the number of ice days, otherwise the model underestimates the occurrence of tropical (TMA ≥ 30°C), warm, and arctic days, and also, it gives higher than observed numbers of frost days. When the model experiments are compared to each other, significant differences are detected mainly in the autumn occurrence of ice and frost days, which are more often in the ARPEGE-Climat experiment, otherwise the performance of the model in both experiments is the same or very similar.

Table 5. Long-term (1961–1990) average of seasonal and annual numbers of rainy days (with daily amount exceeding given threshold) averaged over the Czech Republic in the model experiments (designated according their LBCs), compared with the gridded station. (DJF = winter, MAM = spring, JJA = summer, and SON = autumn)

Season	**Dataset**	**Number of days (PR in mm)**				
		PR > 0	**PR > 1**	**PR > 5**	**PR > 10**	**PR > 20**
DJF	ERA-40	55.4	25.2	8.4	3.1	0.6
	ARPEGE	56.7	29.5	11.2	4.6	1.1
	Stations	45.1	26.2	7.7	2.2	0.3
MAM	ERA-40	66.5	36.7	10.4	3.7	0.8
	ARPEGE	72.2	41.7	13.7	5.9	1.6
	Stations	43.3	27.6	10.2	3.9	0.8
JJA	ERA-40	71.2	50.6	15.7	6.4	2.1
	ARPEGE	75.2	53.7	16.5	6.7	2.2
	Stations	44.7	31.5	15.0	7.2	2.1
SON	ERA-40	49.0	23.1	8.0	3.5	1.0
	ARPEGE	54.8	26.5	9.2	3.8	0.9
	Stations	40.0	24.3	9.2	3.6	0.7
YEAR	ERA-40	242.2	135.7	42.5	16.6	4.5
	ARPEGE	258.9	151.4	50.6	21.0	5.8
	Stations	173.0	109.6	42.1	17.0	3.9

The number of days with precipitation (PR > 0) is always overestimated on 20–70% in the model experiments in all seasons. The ERA-40 experiment captures the seasonal and annual number of days with precipitation over 5, 10, and 20 well, while the ARPEGE-Climat experiment well simulates the occurrence of these precipitation events only in summer and autumn and otherwise it overestimates them. In winter and autumn seasonal number of days with precipitation over 1 mm are close to the observed data in both experiments, while in other seasons they are overestimated by the model. When the model experiments are compared to each other, in the ERA-40 experiment the number of precipitation days are less than in the ARPEGE-Climat experiment and in better accordance with the observed data in most cases.

5. Discussion

Our primary interest was to study the model's performance over a small target region. Therefore, we have not chosen the common available pan-European gridded datasets for model's validation because they offer rather coarse resolution and low density of input information (station data) from which they were created. Instead we took the advantage of the access to the observation data in its best available quality in the studied region, created a new gridded dataset of station observations corresponding to the RCM ALADIN grid at 10 km horizontal resolution in the CECILIA project climate simulations and compared the model's results with it.

As for seasonal mean values, the model is generally in a good accordance with the observed data, although some weaknesses have been identified as well. The spring cold bias of 2-meter temperature detected in both experiments indicates that its origin is rather in the regional model itself than the driving fields. The similar pattern in its extent covering large parts of Central and Eastern Europe, has been already found in the previous, coarse resolution experiments and it has been associated with a snow accumulation over the winter season and consecutive prolonged snow melting during the spring (*Farda et al.*, 2007). On the other hand, the autumn cold bias in the ARPEGE-Climat experiment not corresponding to the positive bias in the ERA-40 experiment is perhaps a consequence of a stronger zonal flow in the driving GCM.

The warm (cold) biases can be also identified in the shift of the mean values of the 2-meter temperature distribution (between the 25th and 75th percentiles) in the model experiments toward warmer (or colder) values, while the same shift is usually found only in one end of the temperature distribution (*Table 3*). When considering the data from *Tables 3* and *4* it appears, that the positive (negative) biases in 2-meter temperature are not usually associated with the significantly increased number of warm (cold) extreme events defined on the base of daily maximum temperature in the model experiments. Certain exception from the above mentioned phenomenon is the reduced number of warm days in spring and arctic days in winter in the model experiments. The spring cold bias is also well expressed in the increased number of frost days.

Positive precipitation biases can be linked with the tendency of the model "to precipitate" more often than in the station measurements (*Table 5*). In all seasons the increased number of rainy days could be attributed to more frequent occurrence of drizzling or little rain with daily precipitation sums ≤ 1 mm (≤ 5 mm in spring and summer).

Although some biases of precipitation and 2-meter temperature in the model experiments can be linked with other phenomena and their sources can be identified either in the regional model or the driving data, further analysis is still needed to confirm these hypotheses.

The studied area is rather small compared to the regions on which the RCMs are often validated, e.g., PRUDENCE project regions. Due to the local variability of climate conditions mainly with the altitude in the selected area, further improvement of the results of the model validation could be achieved by performing the analysis in the sub-regions defined according to the altitude or climate classifications.

6. Conclusions

The presented results of the first evaluation of the historic run experiments performed with the RCM ALADIN-Climate/CZ confirm the findings of previous studies made with the model with coarse resolution, see e.g., *Farda et al.* (2007). The model is capable to capture the main features of the 2-meter temperature and precipitation fields in the region of Central Europe, and it is working well even over smaller areas with a rather complex orography represented here by the territory of the Czech Republic. The overall performance is better when the model is driven by the ERA-40 re-analyses, especially in terms of mean values, however, the results obtained with the model forced by the GCM ARPEGE-Climat are very satisfactory as well. The increased differences between the model driven by GCM and the observed data are mainly due to the use of less perfect driving data than the re-analyses. Nevertheless, some weaknesses and problems in simulating 2-meter temperature and precipitation detected in this study can be attributed directly to the model. It is the spring cold bias caused by winter snow accumulation and later prolonged snow melting in spring of the model or the tendency, to generate more precipitation than in the reality. Although the mean values vary between the described experiments, the analysis of selected characteristics based on daily maximum and minimum temperatures and sums of precipitation have revealed that the model experiments provide results which may differ from the observations, but they are similar when compared to each other.

To validate the model under the high resolution of 10 km, the gridded dataset of the station observations has been created. It is planned to broaden the dataset to cover the region of the common CECILIA target area (CECILIA project: http://www.cecilia-eu.org). Before that, a more detailed investigation of the gridding technique and its affect on the quality of the final dataset is necessary to be carried out, however.

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Transient simulation of the REMO regional climate model and its evaluation over Hungary

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Abstract—A couple of years ago the REMO model originally developed by the Max Planck Institute for Meteorology (MPI-M) in Hamburg was adapted at the Hungarian Meteorological Service with the aim to become an essential tool for providing realistic regional climate estimations for the next few decades particularly for the area of the Carpathian Basin. This area of interest is especially important considering the fact that one of the largest uncertainties in climate projections can be found over the Carpathian Basin, as it had already been identified by former large international climate projects. Various versions of the REMO model have already been tested all over the world for different geographical domains, however, recently further validations and tests have been started also at the Hungarian Meteorological Service in the framework of the CLAVIER EU project. The article is dealing with the 100-year transient simulation of REMO5.0 model for the period 1951–2050. The lateral boundary conditions for the domain covering continental Europe with 25 km horizontal resolution were provided by the ECHAM5/MPI-OM global atmosphere-ocean general circulation model with the use of A1B SRES scenario for the future. On the one hand, present article is dedicated to summarize in detail the validation results of the experiment for the past climate, and on the other hand, to introduce the preliminary climate change estimations based on REMO results for the future. Special emphasis is put on evaluating the performance of the REMO model for the Carpathian Basin in general and for Hungary in particular.

Key-words: regional climate modeling, transient simulation, REMO model, subjective and objective evaluation

1. Introduction

The Earth's climate system is defined (*GARP,* 1975) as being composed of the atmosphere, hydrosphere, cryosphere, land surface, and biosphere, together with their complicated and two-way interactions as further important ingredients,

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playing crucial role in the understanding and determination of the climate. It is generally accepted that the only scientifically sound way to understand the behavior of this complex system and, furthermore, estimate its future evolution is provided by its numerical modeling. In the last half century, more and more sophisticated models were developed in order to describe the individual components of the system and also to take into account the highly non-linear links and feedbacks between these subsystems.

Due to the rapid scientific, technical, and algorithmic evolution of the models and the available enhanced computer power, the horizontal resolution of the global general circulation models developed and exploited by the largest world climate centers reaches nowadays the 100 km range. These models are continuously improving (for instance they possess rather complex physical parameterization schemes), and recently they are providing solid basis and realistic projections for the synoptic scale characteristics of the climate, however, they are at the moment largely insufficient for detailed regional scale estimations. These global projections are not capable to yield detailed and reliable information, e.g., about the summer precipitation over the Carpathian Basin, because their spatial resolution is still far too low to account for such regional phenomena, and on top of it all their ability to describe properly the surface characteristics (typically and most importantly the orography for instance, but other surface features as lakes can be also mentioned) of the area of interest is still limited.

Currently there are three main methods (referred to as regionalization techniques or downscaling methods) for getting improved information about regional climate, and climate change based on the results of the global climate model systems: the application of high and variable resolution general circulation models (*Cubasch et al.*, 1995; *Déqué* and *Piedelievre*, 1995), the use of high resolution limited area regional climate models (*Giorgi* and *Bates*, 1989), and statistical downscaling (*Wilby et al.*, 1998). The first two methods belong to the dynamically-based techniques, where the global results are dynamically refined for obtaining smaller scale climate details. The statistical downscaling procedures are using statistical relations between the global and regional climatic characteristics described for the past and assuming their applicability for the future as well. Hereafter the employment of regional models will be considered and illustrated with the help of the REMO regional climate model.

The limited area models have already been widely and successfully used in the weather forecast for many decades. Their employment for climate "prediction" purposes was arisen in the late 1980s. The first climate simulation with a regional climate model (RCM), which was developed on the basis of a short-range weather forecasting model, was carried out by Giorgi and Bates (1989). The RCM was nested into a global climate simulation, which provided the initial and lateral boundary conditions for the experiment. The following issues regarding this nested modeling approach were investigated in the first experiments:

- Whether the long integration is not accompanied by accumulation of error characteristics in time (one can imagine that even small systematic errors during a climate simulation might accumulate in such a way that destroy the signal otherwise provided by the model);
- Whether the regional model is able to reproduce realistically those synoptic scale features of the climate, which are specified by the lateral boundary conditions;
- Whether the regional model reflects accurately the regional climate statistics.

The experiments supplied positive results, so green light was given for the wide-range employment of limited area models in climate simulations. All this had revolutionary consequences, because the use of regional models really provides an effective way to investigate in the fullest detail the regional aspects of the global climate change due to their finer resolution, better representation of the surface characteristics (topography, land-sea mask, albedo, etc.), and mesoscale processes. Since that time new and new generations of regional climate models were developed and applied: some of them were originated from weather forecasting models, while others were developed based on global counterparts (i.e., global climate models). The aforementioned questions investigated in the pioneering work of Giorgi and Bates are still important issues before starting any meaningful model validation experiments and/or climate change simulations.

Naturally, the validation of regional climate models for the past climate is a crucial ingredient of the work with RCMs. This is coming from the consideration that hopes for successful climate scenario projections can be only considered if the models are already reasonably capable to simulate the past climate. (Certainly this issue is not that straightforward due to the fact, that successful past simulations do not ensure directly that a changing future climate will be also well simulated; the reverse is also true, i.e., bias in the past simulations does not mean that for the future the same bias will surely occur.) In the last decade several international projects have been initiated and then realized in order to explore the strengths and weaknesses of the regional climate models, i.e., what the model parameters are, which can be predicted with larger confidence, and what the regions are, where the climatic characteristics are sufficiently well-described in the simulations. For instance, in the framework of the RAACS project (Regionalization of Anthropogenic Climate Change Simulations; *Machenhauer et al.,* 1998) it was recognized that many regional climate models simulate too dry and too warm summer climate over Central and Eastern Europe for the second half of the 20th century. Later on, in the MERCURE project (Modeling European Regional Climate: Understanding and Reducing Errors) an important objective was to understand and reduce this model bias referred to as summer drying problem (*Hagemann et al.,* 2004). The investigations of the PRUDENCE project (Prediction of Regional scenarios and Uncertainties for Defining European Climate change risks and Effects, *Christensen*, 2005) focused on the comprehensive validation of simulations of ten regional models (using a horizontal resolution of about 50 km) for the period of 1961–1990. The results have shown that the summer warm bias still exists in the majority of the participating RCMs, therefore, unfortunately no model developments in between improved the situation substantially (*Hagemann* and *Jacob*, 2007).

Meanwhile, in order to satisfy the increasing demands, the models are also applied to realize climate change simulations in spite of the known model deficiencies. Therefore, in the ongoing and future works the issues related to the summer drying problem and other model deficiencies should be addressed in an extended perspective, and the following additional questions should be discussed and answered: what is the influence (if any) of the systematic past biases on the climate change signals, what is the relative size of the bias with respect to the real climate change signals, can the differences between the climate change signals of the various models be originated from their different bias characteristics (*Jacob et al.,* 2007)?

As it was indicated above, the summer drying problem is still an open and acute issue strongly influencing the uncertainty of the climate change projections for the Central and Eastern European region. This particular issue together with other aspects related to the uncertainties in climate change projections are addressed within the CLAVIER EU project (Climate ChAnge and Variability: Impact on Central and Eastern EuRope, http://www.clavier-eu.org). In the framework of this project, the LMDZ model (developed by the Institut Pierre Simon Laplace in Paris) and two versions of the REMO model (developed by the Max Planck Institute in Hamburg) were considered in order to provide a small ensemble of regional simulations for the area of interest (mainly the territories of Bulgaria, Hungary, and Romania). Firstly, the models were integrated for a past period (1961–2000) with the use of ERA-40 re-analyses (*Simmons* and *Gibson*, 2000) as lateral boundary conditions in order to explore the main characteristics of the models' behavior in case of "quasi-perfect" driving. It is noted here that the present article does not discuss the results of these "reference" simulations, however, a lot of results were already introduced and reported earlier (see for instance at *Szépszó,* 2008). It was decided that the succeeding climate change simulations are going to focus on the near past and future in a transient manner, therefore, the different REMO-versions (REMO5.7 at the Max Planck Institute in Hamburg and REMO5.0 at the Hungarian Meteorological Service) and the LMDZ model are integrated for the period between 1951 and 2050 using relatively high (10 and 25 km) horizontal resolution. (Hereafter the results of REMO5.0 simulation on 25 km resolution will be introduced and discussed in detail.) The large scale forcings for the regional models are provided by the global fields of the ECHAM5/MPI-OM coupled atmosphere-ocean general circulation model, and in the case of the LMDZ regional model the simulation was repeated with the use of driving fields from its global counterpart. The regional models were forced only with the A1B SRES emission scenario, which is considered as a "realistic" estimate for the evolution of the greenhouse gas concentrations until the end of the 21st century (*Nakicenovic et al.,* 2000). Nevertheless, it is remarked here that basically until 2050 there is no real difference even between the most optimistic emission scenario and the most pessimistic one compared to the natural climate variability and uncertainties in the RCMs.

After this introduction a brief overview is given about the most important characteristics of the ECHAM5/MPI-OM coupled model system and REMO5.0 regional climate model adapted at the Hungarian Meteorological Service. Section 3 deals with the description of the accomplished simulation together with the thorough analysis of the validation results over Europe with special emphasis on the Hungarian territory. The results for the future are also detailed in the same section providing preliminary climate change estimations. In Section 4 several open issues are addressed and discussed together with those major conclusions, which could be drawn based on the results of the transient simulation.

2. *The applied models*

The ECHAM5 (*Roeckner et al.,* 2003) is the current version of the ECHAM models. The ECHAM atmospheric general circulation model has been developed compounding the dynamical part of global weather prediction model of European Centre for Medium-Range Weather Forecasts (therefore, the first part of its name is EC) and a comprehensive parameterization package developed at Max Planck Institute in Hamburg (therefore the abbreviation HAM), which allows the model to be used for climate simulations. The MPI-OM model (*Marsland et al.,* 2003) was developed (also by the MPI-M) based on the HOPE (Hamburg Ocean Primitive Equation) ocean general circulation model and includes also a dynamic-thermodynamic sea-ice submodel.

For the fourth assessment report of the IPCC the coupled ECHAM5/MPI-OM atmosphere-ocean model has been used among other models to provide global climate simulations. The coupled model was run without flux correction at T63 (about 1.875 degree or 200 km) horizontal resolution and 31 vertical levels in the atmosphere, and about 1.5 degree horizontal resolution and 40 vertical layers in the ocean. The model integrations encompass control simulations covering the period 1860–2000 and hundred-year simulations for the future climate from 2001 onwards. For the past climate observed concentrations of CO_2, CH_4, N_2O, CFCs, ozone and sulphate aerosols were taken, while for the 21st century these concentrations were prescribed according to the three IPCC scenarios B1, A1B, and A2 (note that for our investigations exclusively the A1B scenario results were used).

The REMO regional climate model was developed on the basis of the "Europa Model" (the former numerical weather prediction model of the German Weather Service, *Majewski*, 1991) together with the inclusion of the global atmospheric general circulation model ECHAM4's (*Roeckner et al.,* 1996) physical parameterization package.

REMO (*Jacob* and *Podzun,* 1997) is a gridpoint model and the primitive equations are written in advective form in rotated spherical coordinate system. The phase-errors caused by horizontal discretization are reduced by staggered Arakawa grid (C-type) (*Mesinger* and *Arakawa,* 1976). The prognostic variables of the model are the temperature, horizontal wind-components, specific humidity, and cloud water content on the model levels and the surface pressure. In vertical a hybrid coordinate system is defined (*Simmons* and *Burridge,* 1981). The maximum number of vertical levels in the model is 49 (for our experiments 20 levels were used). At the moment only the hydrostatic model version is available, therefore, the highest possible, plausible resolution of the model is about 10 km. Due to the Eulerian treatment of advection, the longest possible timestep, used at the highest resolution is 45 seconds. For the appropriate treatment of the lateral boundary conditions the model uses the classical Davies' scheme (*Davies,* 1976).

In the REMO version adapted at the Hungarian Meteorological Service (REMO5.0) the description of the thermal and hydrological processes in the soil follows the ECHAM4's schemes: the temporal evolutions of the soil temperature and the soil water content are predicted by solving the diffusion equation using a five-layer model (*Warrilow et al.,* 1986); the vertical diffusion and surface turbulent fluxes are calculated based on the Monin–Obukhov similarity theory (*Monin* and *Obukhov*, 1954); the runoff scheme is based on catchment consideration including sub-grid scale variations of field capacity over inhomogeneous terrain (*Dümenil* and *Todini,* 1992). The parameterization of radiation processes is called every hour during the model integration: the description of short-wave radiation follows the method developed by *Fouquart* and *Bonnell* (1980) in two spectral intervals; for the longwave the model uses the narrow-band model after *Morcrette et al.* (1986) with several modifications for additional greenhouse gases and various types of aerosols. The large scale cloud and precipitation formation are calculated based on the budget equations of total cloud water (including cloud liquid water and cloud ice with a simple diagnostic formulation for the latter one) and water vapor, taking into account sources and sinks due to advective and sub-grid scale moisture transports, condensation of water vapor, precipitation formation by coalescence of cloud droplets and sedimentation of ice crystals, evaporation of cloud water and precipitation in unsaturated air (*Sundquist*, 1978). The parameterization of the moist convection is based on a mass flux scheme (*Tiedtke,* 1989) including three types of convection, but it contains also several improvements described by *Nordeng* (1994).

The physical parameterization packages of REMO5.0 and ECHAM5 are mainly consistent, since in REMO5.0 the schemes of ECHAM4 were implemented, however, the 5th generation of ECHAM model includes several improvements (e.g., a prognostic equation for cloud ice content instead of the former diagnostic formulation).

3. *Investigations for the Carpathian Basin*

3.1. Experimental design

The model domain applied at the Hungarian Meteorological Service (OMSZ) covers large part of the continental Europe (*Fig. 1*): it certainly includes the entire Central and Eastern European region of interest with sufficiently large extension towards west (the main direction of flow). Furthermore, care was taken to ensure that the lateral boundaries of the domain are in relatively far distance from the high mountain ranges (especially from the Alps and the Carpathian Mountains). The horizontal resolution of the integration domain is approximately 25 km (exactly 0.22 degree), which allows 2 minutes integration timestep. The global fields were coupled to the limited area with 6-hour temporal frequency.

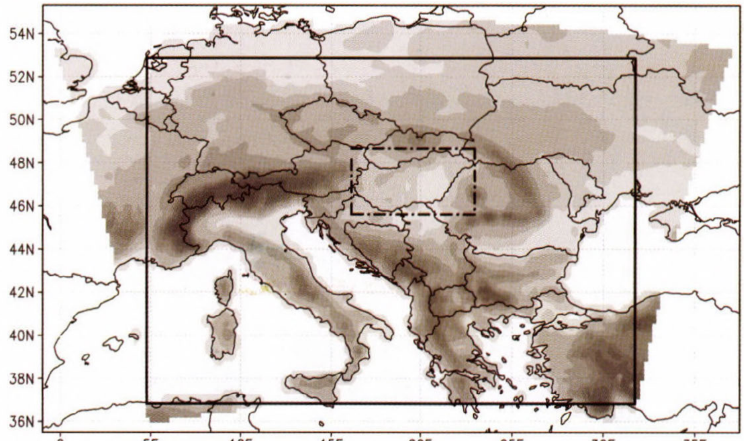

Fig. 1. Orography of the REMO domain used for the long transient climate change simulation (1951–2050). The domain consists of 101×81 gridpoints and its horizontal resolution is approximately 25 km (exactly 0.22 degree). The large (solid) rectangle represents the evaluation domain with respect to the CRU dataset and the small (chained) one indicates the verification area with respect to the Hungarian gridded dataset.

First of all, the performance of the model is validated with respect to various "observational" data in order to understand the model's behavior for the past, which is considered as valuable information for evaluating the simulations for the future. For that purpose the model results are verified for the period of 1961–1990 with the 10-minute (approximately 20 km) version of CRU database (*Mitchell et al.,* 2004) for the European region and with the gridded (0.1 degree resolution) Hungarian observational dataset over Hungary. The application of the latter dataset is justified by the suspicion that the CRU database might not be sufficiently precise over our main area of interest (i.e., Hungary), because of the less local data used for its constitution. The gridded Hungarian dataset (hereafter referred to as HUGRID) is based on Hungarian surface measurements post-processed by the so-called MISH (Meteorological Interpolation based on Surface Homogenized Data Basis) special interpolation technique (*Szentimrey* and *Bihari*, 2005), where the irregularly distributed observations are interpolated to a 0.1-degree resolution latitude-longitude grid covering Hungary using also climatic information based on long observational time series.

The evaluation is concentrating on the differences between the model results and the observational data for two main parameters: 2-meter mean temperature and precipitation amount. Besides the departure and standard deviation fields (the latter ones are not shown in the article) visualized at monthly, seasonal, and annual scale, also several objective statistical characteristics (e.g., mean error, root mean square error) are calculated focusing on the region of our interest (Hungary).

3.2. Validation results for the past climate

Regarding the general flavor of the results, having a look at the annual departure fields of mean temperature and precipitation, as a basic conclusion one can say, while the model provides quite realistic temperature distributions almost everywhere in the domain, it results too high precipitation amounts over large part of the area. (So the model is rather correct in temperature, but at the same time too wet.)

Temperature

Generally speaking, the annual temperature differences between the model results and the (CRU) observations (*Fig. 2*) are rather small (indicating rather perfect simulation), remaining under 1 °C over the major part of the domain, which is especially true for our region of main interest (over Hungary). Exceptions can be noticed over the Alpine region and southeast from the Carpathian Basin: whilst in the elevated points the model underestimates the annual mean temperature, over the southeastern region it predicts too warm climate for the reference period 1961–1990 (it can be remarked that even at that "critical" areas the errors do not exceed 3 °C).

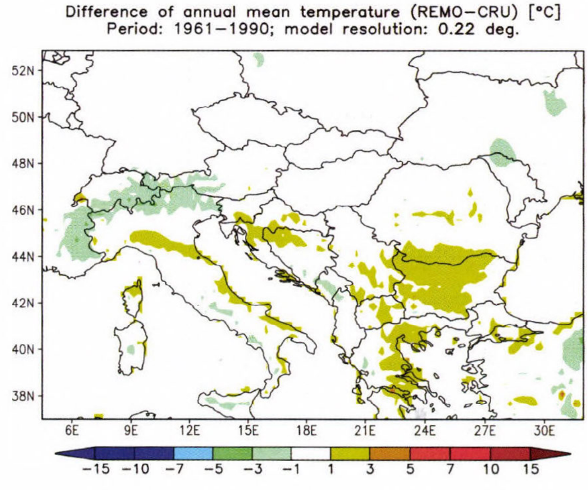

Fig. 2. Difference (in °C) of the annual mean (2-meter) temperature between the model results and the 10-minute resolution CRU dataset for the period of 1961–1990. The intercomparison was carried out on the 0.22 degree resolution re-rotated model grid.

Comparing the mean temperature in the regional model and the driving ECHAM5/MPI-OM global model (*Fig. 3*), it can be generally pinpointed (as anticipated), that the similar large scale features of both models are refined in terms of spatial details by the regional model. It can be clearly seen that due to the more exact description of orography and land-sea mask, the REMO model reflects the temperature patterns of the higher mountains (e.g., the Alps, the Carpathians, and the Dinaric Alps) and the land-sea "contours" (see Apennine Peninsula for instance) more realistically than the global one.

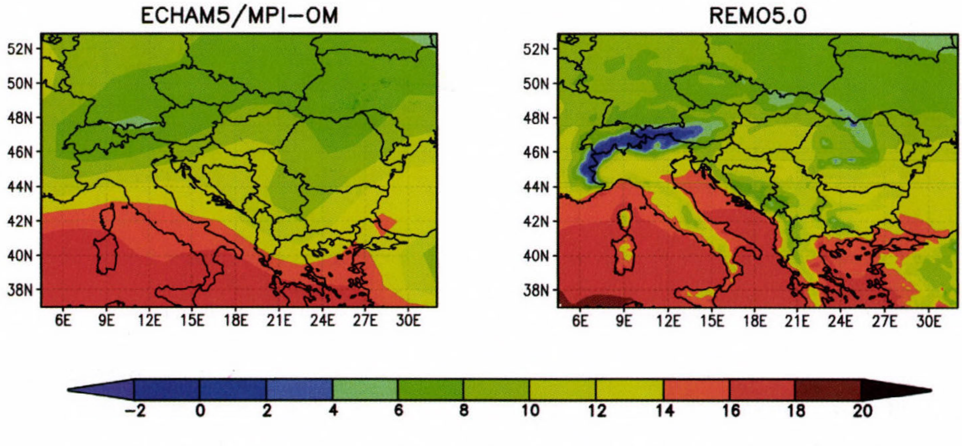

Fig. 3. The annual mean (2-meter) temperature (in °C) in the results of ECHAM5/MPI-OM global model and ECHAM5/MPI-OM-driven REMO5.0 regional model for 1961–1990. The maps indicate the original model resolutions.

Looking at the seasonal details (*Fig. 4*), the main characteristics of the annual pattern are still visible (underestimation at the Alps and overestimation over Bulgaria). The best seasons are autumn and spring (with slight preference towards spring) in terms of deviations from the CRU data. The behavior of the model for the main seasons (winter and summer) is quite different: in winter mostly overestimation can be seen except some mountainous (the Alpine region) and coastal (around the Mediterranean Sea) regions; in summer the model domain is decomposed into two parts: underestimation on the North and overestimation over the South.

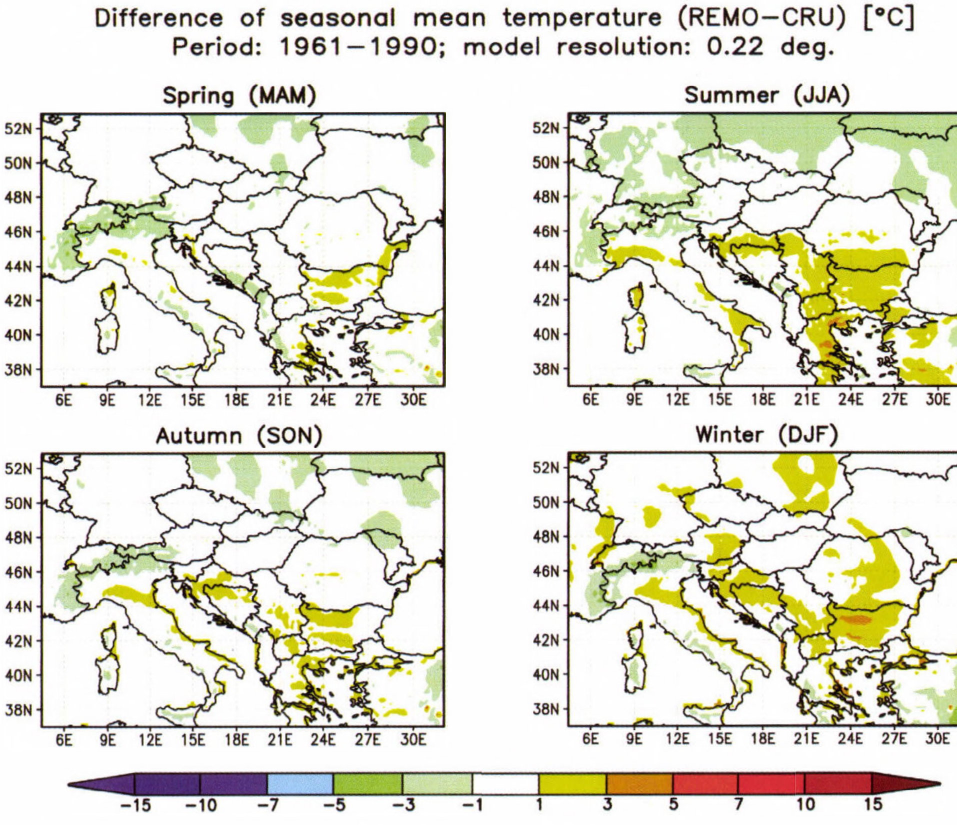

Fig. 4. Difference (in °C) of the seasonal mean (2-meter) temperature between the model results and the 10-minute resolution CRU dataset for the period of 1961–1990 The intercomparison was carried out on the 0.22 degree resolution re-rotated model grid.

The monthly figures (not shown) bring some additional details: the temperature fields of REMO are especially warm during December and January (especially South of the Carpathian Basin), whereas for April and May the smallest bias can be noticed. The winter overestimation is gradually reduced towards the coming spring months. The leading errors during the summer are in August, when both positive and negative areas can be concluded (the above-mentioned bimodal pattern between the northern and southern part of the domain).

Focusing on the performance of REMO5.0 over Hungary and concentrating on objective scores it can be seen, that the annual mean temperature simulated by the model is almost perfect with respect to the CRU-dataset (*Table 1*): its annual bias is –0.01 °C. Seasonally the simulations are mainly too cool (the only exception is the winter period, when a slight positive bias can be seen), but the errors never reach the 0.5 °C. In spite of the best performance in spring for the entire domain (see above), this season is the worst in terms of bias with respect to CRU over Hungary. The best simulations over Hungary occur in summer as it is also confirmed by the root mean square error values (*Table 2*). The differences (biases) are a bit larger if the validation is realized against the Hungarian gridded observational dataset (but they are still modest remaining mainly under 0.5 °C). It is interesting to see that although the magnitude of the biases with respect to the CRU and HUGRID are similarly small, for the CRU rather the underestimation, while for the Hungarian dataset rather the overestimation is typical. (This means that although the differences between the CRU and Hungarian datasets are small, due to the small bias values this slight deviation might cause different direction of the bias.) The density functions for the differences (not shown) provide some additional insight into the distribution of the seasonal errors with respect to the Hungarian observations: the bias range covers the –1.5 – +1.5 °C interval in general, however, in particular the errors occur mostly between –1 and 1 °C all over the year.

Table 1. The annual and seasonal differences (biases) between the REMO5.0 simulation and the different reference (CRU and HUGRID) datasets, and the ECHAM5/MPI-OM global model averaged over Hungary for 2-meter temperature and precipitation. The values are valid for the period of 1961–1990

	Mean differences (biases)									
	Mean 2-meter temperature [°C]					**Precipitation [mm/month]**				
	Annual	**MAM**	**JJA**	**SON**	**DJF**	**Annual**	**MAM**	**JJA**	**SON**	**DJF**
REMO-CRU	–0.01	–0.43	–0.05	–0.11	0.26	7.68	16.81	–1.94	7.50	8.07
REMO-HU	0.21	–0.22	0.14	0.44	0.52	8.05	16.07	–0.62	8.70	8.42
REMO-ECHAM	0.92	0.83	1.16	1.12	0.55	8.36	6.43	21.28	7.19	–1.52

The mean difference between the (regional) REMO and the (global) ECHAM5/MPI-OM models (*Table 1*) shows that the temperature prediction of REMO is warmer than that of the global one. This departure is the lowest in winter, however, it is always only around 1 °C. In spite of the fact, that the biases between the two models are larger than those between the models and the observations, the root mean square values indicate that the inter-annual variability between the models is more similar than it is the case between the models and the observations. This is somehow understandable, because in the temporal trends the boundary conditions are important "constraints" for the regional model and most probably the models are unable to simulate the inter-annual variability with sufficient preciseness. For any case generally it can be concluded, that over Hungary the results of REMO model are slightly cooler than the CRU observations, however, the regional model is still warmer compared to the global driving fields (so the global model is even cooler). It was the case also at the simulation driven by ERA-40 data (i.e., the regional results were warmer than the global ones), so it seems that the REMO model introduces a systematic heating effect into the large scale fields, however, in the re-analyses-driven case REMO overheated the temperature fields with respect to the observations.

Table 2. Root mean square errors between annual and seasonal results of REMO5.0 simulation and the different reference datasets (CRU and HUGRID), and the ECHAM5/MPI-OM global model averaged over Hungary for 2-meter temperature and precipitation. The values are valid for the period of 1961–1990

	Root mean square error									
	Mean 2-meter temperature [°C]					**Precipitation [mm/month]**				
	Annual	**MAM**	**JJA**	**SON**	**DJF**	**Annual**	**MAM**	**JJA**	**SON**	**DJF**
REMO-CRU	1.15	1.67	1.30	1.43	2.49	16.63	28.57	29.96	23.63	18.87
REMO-HU	1.14	1.60	1.28	1.53	2.50	17.57	28.37	31.52	25.29	20.37
REMO-ECHAM	1.07	1.04	1.31	1.33	1.02	10.35	13.85	25.06	14.59	10.84

Precipitation

As far as the relative differences of the annual precipitation fields are concerned (*Fig. 5*), besides the general wet characteristics, the orographic features can be immediately noticed: around the highest peaks in Europe (the Swiss, Italian, and Austrian ranges of the Alps) the precipitation overestimation is the strongest (exceeding even 200 percent of the observed values). It is noted that the exact location of this overestimation is not over the mountain peaks, but rather over the slopes. The situation is qualitatively similar for the Carpathian ridge, however, the overestimation is much less pronounced (its magnitude remains "only" between 50 and 100 percent). Curiously, opposite tendencies can be detected in other elevated parts of Europe, like the Adriatic side of the Alps, the Dinaric Alps, the Apennines, or the southern ranges of the Carpathians: the underestimation varies between 10 and 50 percent. As far as Hungary is concerned, also here the too much humidity is dominant (as it is the case for almost all along the domain): the model predicts more precipitation (mainly with 10–50 percent) than the observed annual mean (but the situation is not as bad as at some other parts of the domain).

Comparing the mean precipitation in the regional (REMO) and the global driving (ECHAM5/MPI-OM) model (*Fig. 6*), the situation is (not surprisingly) similar to that of for the temperature: the large scale features are regionally refined by REMO most particularly over the mountain ranges. Generally speaking, the regional model is significantly more humid than the global one, especially over the highest mountains and in the vicinity of the northern boundary of the integration domain. This latter feature might caused by some "unbalances" between the global and regional fields, while the mountainous humid behavior might stem from the fact that the resolution of the regional model is meaningfully higher, resulting in more precipitation than it is the case for the coarser resolution global model.

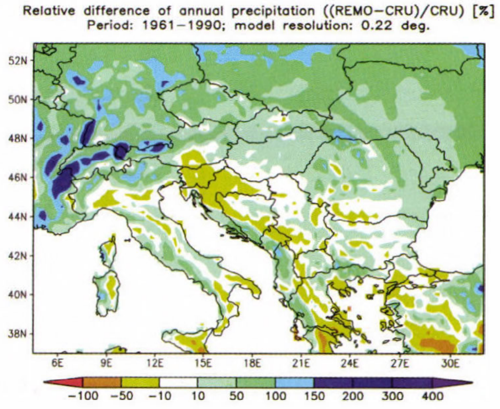

Fig. 5. Relative difference (in percentage) of the annual precipitation between the model results and the 10-minute resolution CRU dataset (reference: CRU dataset) for the period of 1961–1990. The intercomparison was carried out on the 0.22 degree resolution re-rotated model grid.

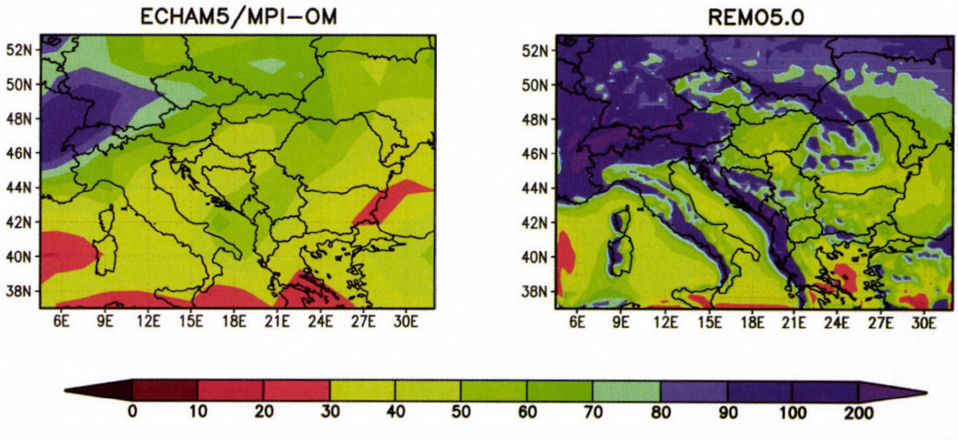

Fig. 6. The annual mean precipitation (in mm/month) in the results of ECHAM5/MPI-OM global model and REMO5.0 regional model for 1961–1990. The maps indicate the original model resolutions.

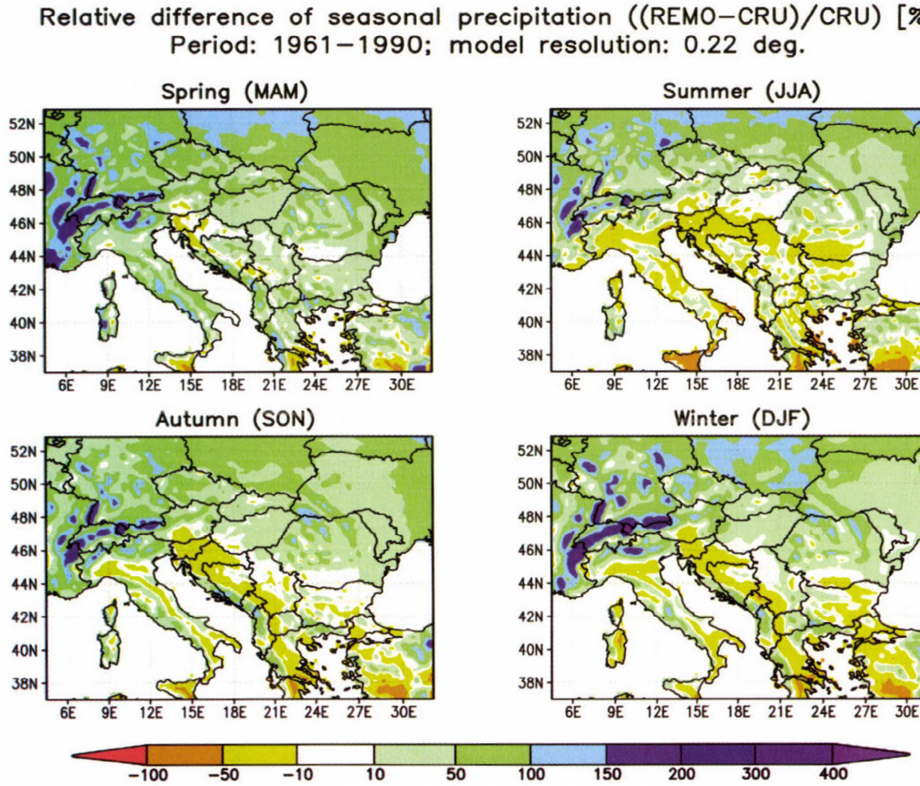

Fig. 7. Relative difference (in %) of the seasonal precipitation between the model results and the 10-minute resolution CRU dataset (reference: CRU dataset) for the period of 1961–1990. The intercomparison was carried out on the 0.22 degree resolution re-rotated model grid.

Investigating the seasonal relative differences between the model results and the CRU-dataset (*Fig. 7*), it can be said, that the seasonal distributions of the departure fields are basically similar to the annual case with some small differences. In spring the overestimation is really dominant, with some very few spotty regions (near to the coastal areas, especially at the Adriatic Sea) with underestimation. On the contrary, in summer while at the northern part of the domain overestimation is dominant, the drying in the model at the South is rather extended. In autumn both the positive errors in the North and the negative errors in the South are decreased (the latter is with respect to the summer situation), whilst in winter the magnitude of overestimation over the Alpine region and the northern part of the domain is strengthened to a "dramatic" level exceeding even 100–200% again. These figures (maybe except the spring one, but especially the summer one) indicate that the Carpathian Basin is situated in an "intermediate" zone, which separates the areas characterized by overestimation over the North and the regions of underestimation over the South. This fact is in agreement with former studies (e.g., PRUDENCE, *Déqué et al.,* 2007, *Jacob et al.,* 2007), where the northerly wet regions and the southerly dry ones are split around the Carpathian Basin, anticipating the serious difficulties for the provision of reliable precipitation estimates for the Carpathian Basin in general and for Hungary in particular. Otherwise, the simulation for Hungary is fairly satisfactory (especially in summer): the departures from the observations generally remain mainly between 10 and 50% (both in positive and negative orientation, however, the positive ones are dominating especially in spring).

The departure fields for the monthly precipitation amounts (not shown) largely support the conclusions of the seasonal results, namely, that the REMO model overestimates the precipitation over the northern part of the region (especially in winter and spring); and underestimates over the southern part of the continent (especially in summer). The largest negative anomalies can be found in June, August, September, and December and the strongest overestimations occur from January to April.

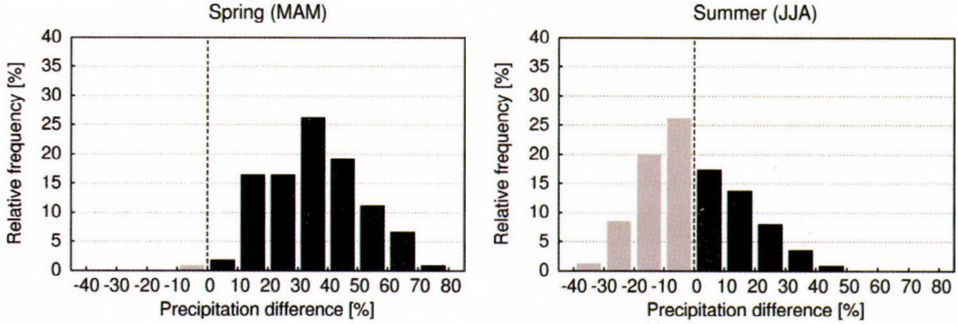

Fig. 8. Discrete density function (in percentage) of the seasonal relative departures (in percentage) for precipitation between the model results and the gridded Hungarian dataset over Hungary for the period of 1961–1990. The dashed line represents the value of 0 percent separating the ranges of over- and underestimation.

Examining the model's behavior over Hungary in terms of objective scores (*Table 1*) one can conclude, that REMO predicts too humid climate (except for summer, when a slight underestimation is exists) for the past compared both to the CRU and the Hungarian gridded observational datasets: the departure is about 8 mm/month on annual scale (contrary to temperature, the error characteristics for the comparison to the two datasets are rather similar). The largest (positive) errors are produced in spring with around 17 mm/month. Basically, the error density functions (*Fig. 8*) confirm these findings, together with some additional information regarding the range and frequency of the model inaccuracies over Hungary. One can easily notice (comparing the above referred maps and histograms), that the span of the over- and underestimation ranges is narrower over Hungary than at the other parts of the integration domain: it varies between 0 and 80% for the overestimation and 0 and 40% for the underestimation. In spring the abovementioned large positive bias with approximately 16 mm/month means 10–70% overestimation. The particularly low error in summer (seen from the bias values over Hungary) is due to the compensation between the over- and underestimated regions of the country (i.e., the almost symmetric arrangement of the histograms).

Looking at the mean annual difference between the precipitation results of the regional and the global model (*Table 1*), a positive deviation can be found with similar magnitude as it is the case with respect to the observations. But carefully scrutinizing the seasonal departures, some other characteristics can be also noticed: the regional model is more humid than the driving global model (as already mentioned above) with a maximum in summer, when the departure exceeds 20 mm/month. The best correspondence between the global and regional results is in winter, when the global model is slightly wetter (the difference is around 2 mm/month). The relatively lower values of the root mean square departures between the two simulated results (*Table 2*) point to the higher variability of errors with respect to the observations, i.e., in the simulated cases the regional results deviate quite systematically (positively) from the global ones, while compared to the observations, the positive and negative errors rather compensate each other as the lower bias values indicate.

Generally it can be concluded, that over Hungary the REMO model is wetter than the global driving fields, which results in too humid features compared to the various observational datasets.

3.3. Preliminary climate change signals over Hungary

The present part of the article is dedicated to introduce what kind of near future changes can be expected over Hungary according to the results of the transient model simulations (the global and the regional one), whose validations were detailed in the previous subsection. The ensuing evaluation is based on the transient integration considering the "classical" reference period (1961–1990) for the past and the period of 2021–2050 for the future. Therefore, the described changes hereafter are always considered with respect to the model reference (the changes with respect to the observations are not discussed). This approach has the advantage that in case of equal model biases for the past and future periods, the subtraction of the future and past values diminishes those biases in the climate change signals (it is a rather commonly accepted approach in spite of its possible weaknesses, therefore, it was also adapted to our use). The forthcoming evaluation is concentrating on the two basic parameters already investigated above: 2-meter mean temperature and precipitation amount.

Temperature

The main and general orientation of the temperature change is quite clear (see *Figs. 9* and *10*): for the period of 2021–2050 an overall temperature increase is projected (either for annual or seasonal means). Nevertheless, some special features can be noticed between the global and regional results and also in terms of temporal (seasonal) and spatial details.

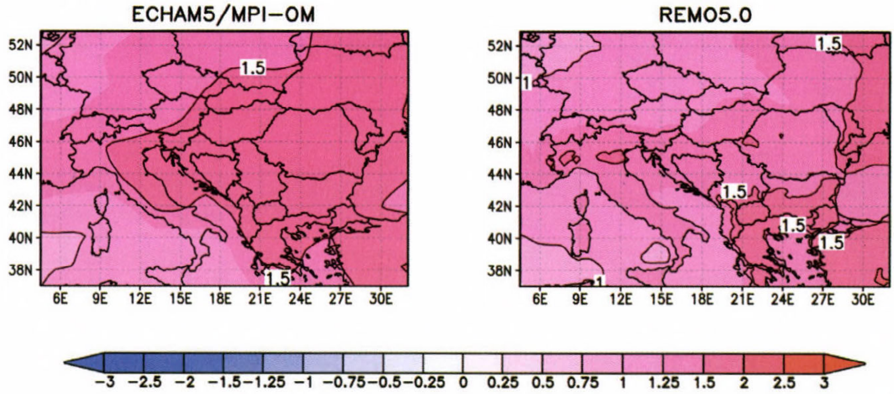

Fig. 9. Change (in ºC) of the annual mean (2-meter) temperature projected by the global ECHAM5/MPI-OM coupled model system and by REMO5.0 for the period of 2021–2050 with respect to the period of 1961–1990.

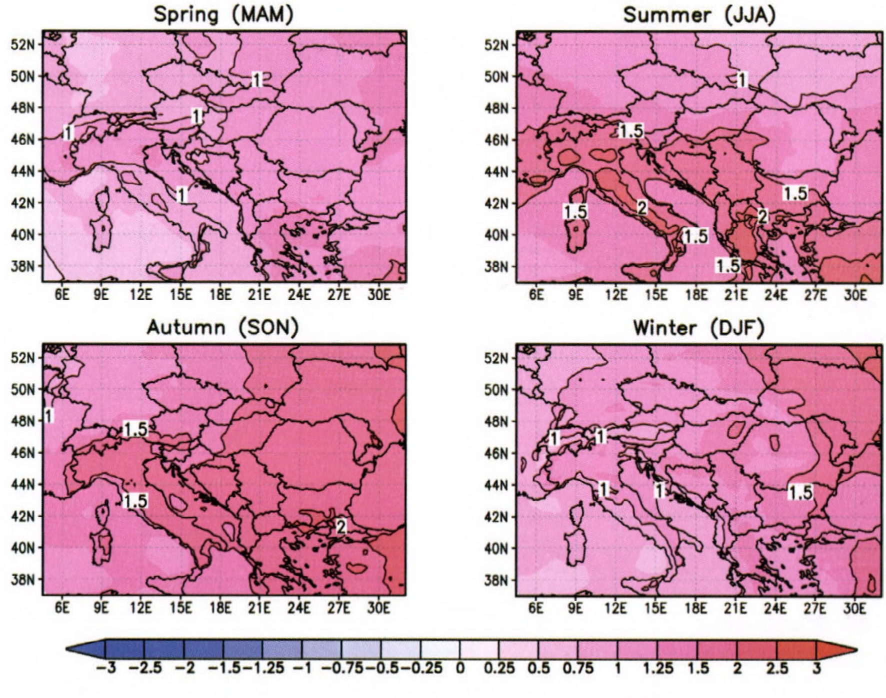

Fig. 10. Change (in ºC) of the seasonal mean (2-meter) temperature projected by REMO5.0 for the period of 2021–2050 with respect to the period of 1961–1990.

First, looking at the "driving" global fields (first panel of *Fig. 9*), it can be seen, that the annual temperature change of a given location is mainly affected by its distance from the ocean, i.e., the warming is more intensive inside the continent (especially over Hungary). This characteristic appears also in the seasonal results except for summer (not shown), when the signal is rather influenced by the latitudinal position of the point: over the southern part of Europe the temperature change exceeds the 2 °C, while over the northern (cooler) part of the continent, the increase remains between 1 and 1.5 °C (in other words the warming will be stronger in the South than in the North during the summer). Regarding the regional results, similarly to the global ones, annual and generally seasonal east-west gradient of change can be noticed (right panel of *Fig. 9* and *Fig. 10*), while at the summer also a north-south gradient appears. As far as the magnitude of the increase is concerned it can be pinpointed, that for the REMO model slightly lower temperature growth can be seen than it is the case for ECHAM. The difference between the two simulations is more spectacular, especially during the summer and autumn, when the regional model projects 1–2 °C change over Hungary, whereas the global model covers the interval of 1.75–2.5 °C (note that this conclusion can be also easily seen quantitatively in *Table 3*).

Table 3. Annual and seasonal change and standard deviation of the annual mean (2-meter) temperature (in °C) and precipitation (in percentage) over Hungary projected by REMO5.0 and ECHAM5/MPI-OM for the period of 2021–2050 with respect to the period of 1961–1990. The latter panel of table represents the annual and seasonal mean differences between REMO 5.0 and ECHAM5/MPI-OM for the period of 2021–2050 (in °C for temperature and mm/month for precipitation).

	Target: 2021–2050, reference: 1961–1990									
	REMO					**ECHAM**				
Change	**Annual**	**MAM**	**JJA**	**SON**	**DJF**	**Annual**	**MAM**	**JJA**	**SON**	**DJF**
Temperature	1.35	1.08	1.35	1.58	1.34	1.73	1.33	1.91	2.07	1.51
Precipitation	–0.91	–7.10	–4.83	2.98	7.24	–3.61	–6.17	–15.30	0.32	5.32
Standard deviation	**Annual**	**MAM**	**JJA**	**SON**	**DJF**	**Annual**	**MAM**	**JJA**	**SON**	**DJF**
Temperature	1.01	1.20	1.33	1.54	1.60	1.08	1.23	1.59	1.67	1.70
Precipitation	17.33	21.10	28.96	32.81	28.22	20.23	30.48	40.71	39.57	32.97
REMO–ECHAM	**Annual**	**MAM**	**JJA**	**SON**	**DJF**					
Temperature	0.54	0.58	0.60	0.64	0.37					
Precipitation	9.63	5.51	24.76	8.81	–0.81					

Concentrating uniquely on the changes over Hungary (*Table 3*), REMO indicates, that the temperature will increase with approximately 1.4 °C in annual mean, and with 1.1, 1.4, 1.6, 1.3 °C in spring, summer, autumn, and winter, respectively. It is interesting to see that this warming is not an obviously temporally linear process, i.e., there is quite significant inter-annual variability considering both the annual (*Fig. 11*) and seasonal (*Fig. 12*) trends. All this implies, that although the general trend shows temperature increase, this does not mean that all the forthcoming years will be warmer than the reference (even at the second part of the projected period there might be years with near-reference or even below-reference values). Nevertheless, it seems that the signal for temperature is rather robust based on the REMO simulations. It is also noted here that one has to be careful with the interpretation of the annual behavior of the model, because although it is expected that the 30-year averages are correctly reflected by the model, it does not mean that the inter-annual variability is also properly addressed.

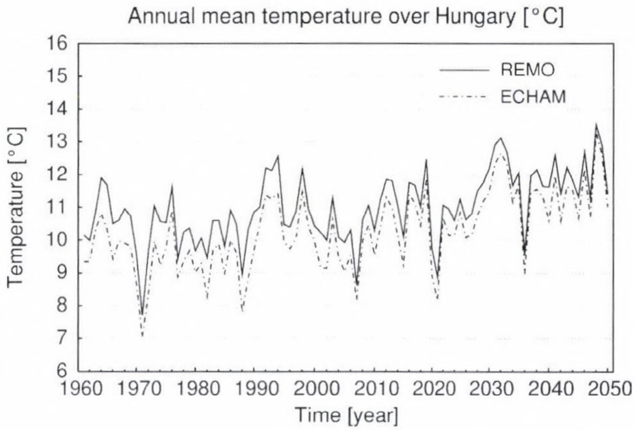

Fig. 11. The annual mean (2-meter) temperature in the results of ECHAM5/MPI-OM global model (chained curve) and ECHAM5/MPI-OM-driven REMO5.0 regional model (solid curve) focused on Hungary for the period 1961–2050.

Certainly besides the relative changes, it is also fascinating to look at the absolute values. According to these (not shown), the main "initial" structure of the temperature fields over Hungary will be conserved at every season (north-south gradient with higher values in the southern regions), however, the temperature values are shifted with 1 °C towards the higher ones. Comparing again the global and regional results for the evolution of the annual mean temperature (*Fig. 11*), it is visible that the difference between the two models is diminishing in the course of time (and it was also quantitatively confirmed by the values regarding the mean deviation between the regional and global fields in *Tables 2* and *3*), because during the reference period the difference between the two models is around 1 °C, then for the future this departure decreases to approximately 0.5 °C (almost vanishing by the end of the integration period) over Hungary. However, the "trend" within the single 30-year periods should be interpreted with special care, because of the fact that the mean signal projected by the regional climate model can not be "split" for individual years.

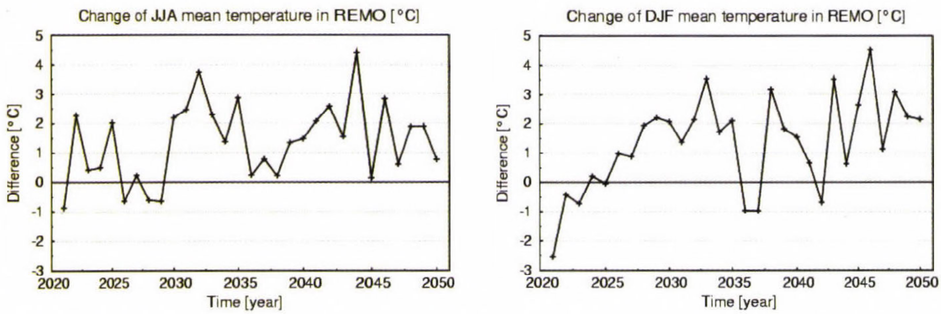

Fig. 12. Evolution of the seasonal (2-meter) temperature change over Hungary projected by REMO5.0 for the period of 2021–2050 with respect to the period of 1961–1990 (left: summer, right: winter).

Precipitation

Regarding the annual precipitation amount, only small changes are projected for the 2021–2050 period by the global and regional models (*Fig. 13*): the precipitation reduction is a bit more characteristic for the entire domain, however, the changes are around –10 and 10 percent in average and maximum –20% in certain regions. As far as the geographical distribution is concerned, at the northern regions of Europe and for the areas being relatively far from the Atlantic-ocean precipitation increase is projected, while over the southern part of the continent and over the Carpathian Basin slight drying can be expected.

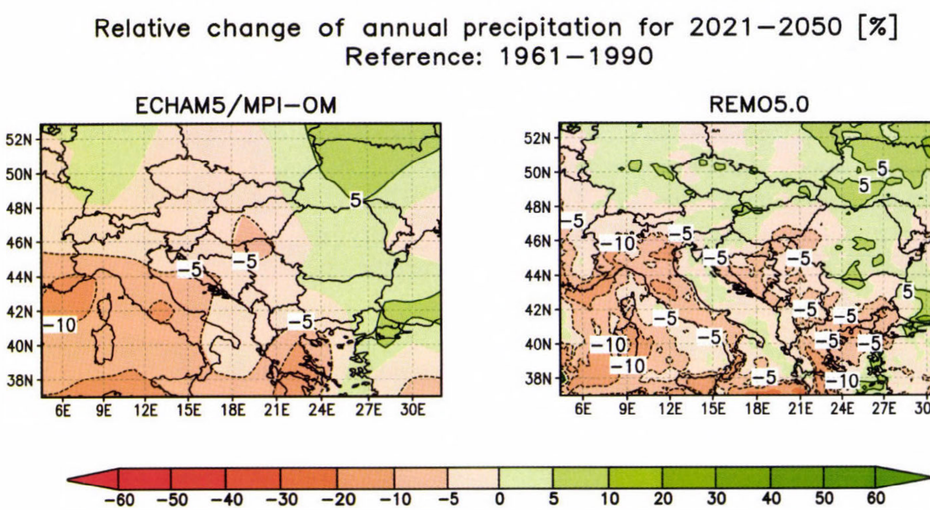

Fig. 13. Relative change (in percentage) of the annual mean precipitation projected by the global ECHAM5/MPI-OM coupled model system and by REMO5.0 for the period of 2021–2050 with respect to the period of 1961–1990.

The global and regional results are in good agreement with each other, however, there are also some differences, e.g., north from Hungary the global model projects drying for the future, whereas REMO renders rather increasing precipitation (this can be probably explained by better description of the mountain ranges over Slovakia and Czech Republic by the regional model).

The seasonal details of the precipitation change are far more interesting than that of the annual ones: there is a large seasonal variability, and therefore, the projected seasonal absolute precipitation values rearrange the whole annual precipitation distribution of the Central European region. Generally speaking, in spring and summer (*Fig. 14*) the precipitation will be reduced for the middle part of the 21st century. Nevertheless, there are also some exceptions: e.g., Northeastern Europe, the highly elevated orographic features like the ranges of Carpathians, where rather increasing precipitation can be foreseen. In autumn the increase will be more overwhelming, especially over the northern part of the domain, while in the South and Southwest rather some drying will take place. Winter is characterized by rather uniform increasing pattern almost all over the domain.

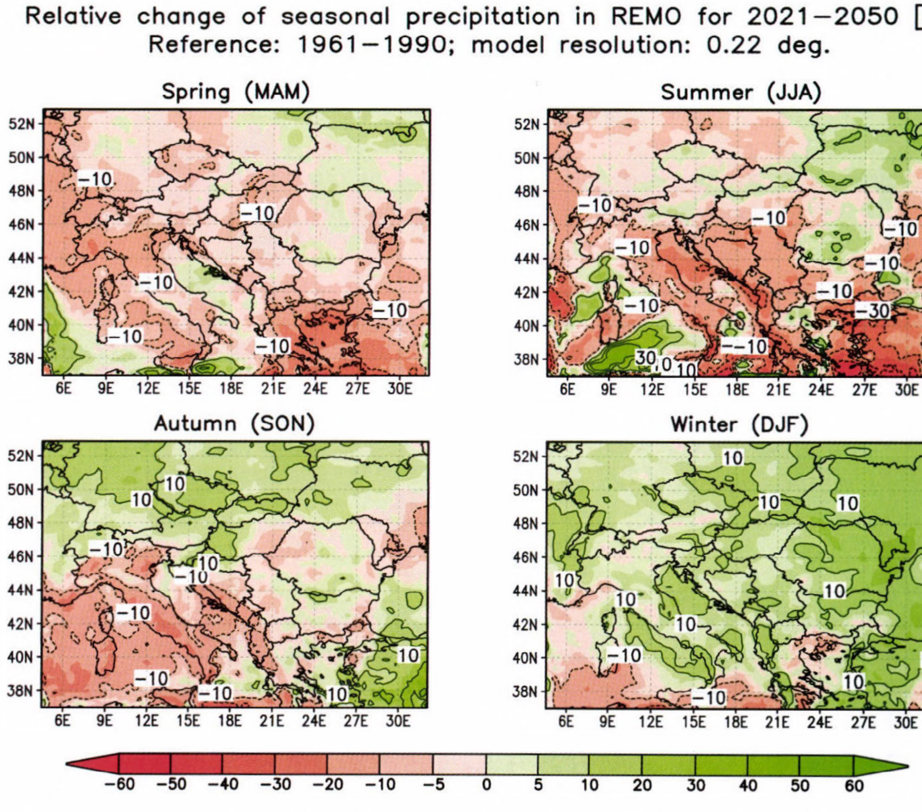

Fig. 14. Relative change (in percentage) of the seasonal mean precipitation projected by REMO5.0 for the period of 2021–2050 with respect to the period of 1961–1990.

The overall magnitude of the likely decrease is slightly larger than the expected increase: in summer the reduction in the global results (not shown) reaches even the 30–50% over the southernmost regions, whilst in winter the increase remains below 20 percent (at that point one also has to consider, that the amount of the winter precipitation is less than the summer one, so the summer "drying" in terms of absolute values will be stronger than the winter growth). Examining the regional results (*Fig. 14*) one can generally say, that the main characteristics of the changes projected by the REMO model is consistent with the results of the ECHAM5/MPI-OM model system, however, a slightly moderate drying is projected for summer over Southern Europe (it reaches only 20–40% over the southern regions) and at the same time (i.e., in summer) the regional results indicate some increase over the highly elevated part of the continent due to its better representation of the regional topographical details.

Furthermore, scrutinizing the REMO results just particularly over Hungary (*Table 3*) it seems, that the relative changes are –7.1, –4.8, 3, and 7.2% in spring, summer, autumn, and winter, respectively, resulting an annual 0.9 percent decrease. These values indicate, that on the one hand, the relative reduction is larger in spring than in summer, and on the other hand, in autumn the precipitation enhancement over the western part of the country and the opposite tendency in East produce an increase in average over Hungary. These findings are rather interesting considering the fact, that recently the most precipitation is falling during the summer and the least one during the winter. The projected changes anticipate that this twofold pattern will significantly change in the future with a more uniform precipitation distribution over Central Europe in general and for Hungary in particular. The inter-annual precipitation changes (*Fig. 15* and *16*) indicate even more fascinating features than it was the case for the temperature: even for those seasons, when the sign of change is rather clear there are lots of years, when the precipitation amount is just the opposite as it would be anticipated by the general average trend (for instance in spring, when the strongest negative change can be concluded, there are several years, when the precipitation is above the reference mean or in winter, when the highest increasing tendency can be seen, there are plenty of years with below average precipitation amounts). All this indicates and proves that an "unusual" season does not provide any direct hint towards the tendencies of the climate change. The abovementioned inter-annual variability is valid not only for the regional model, but it can be noticed also in the global fields (*Fig. 15*). The general temporal evolution of the annual mean precipitation is quite similar in the two models for the past and for the future as well, however, the differences between the global and regional simulated results show an increasing tendency coming from the past towards the future (the opposite trend was found for the temperature).

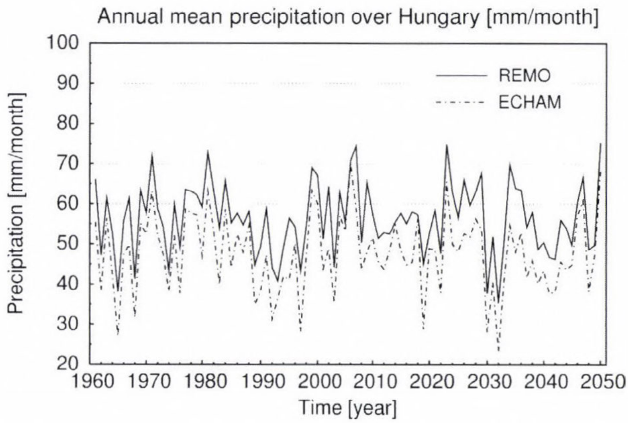

Fig. 15. The annual mean precipitation in the results of ECHAM5/MPI-OM global model (chained curve) and ECHAM5/MPI-OM-driven REMO5.0 regional model (solid curve) focused on Hungary for the period 1961–2050.

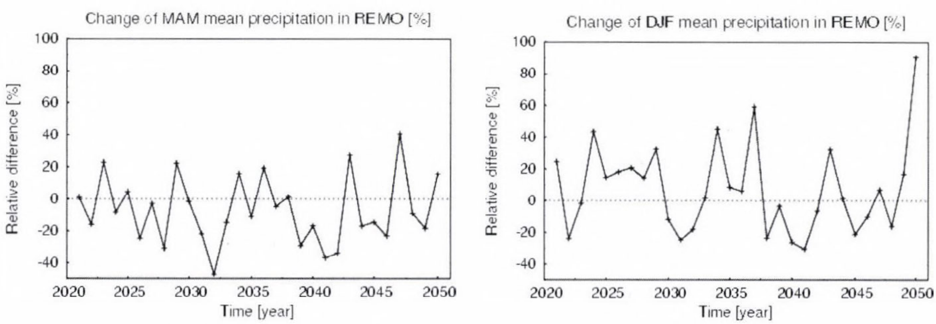

Fig. 16. Evolution of the relative seasonal precipitation change over Hungary projected by REMO5.0 for the period of 2021–2050 with respect to the period of 1961–1990 (left: spring, right: winter).

In the case of precipitation, the absolute precipitation amounts are important information in order to understand the exact quantitative characteristics of the expected changes. For instance, a relative 10 percent change might have rather different consequences for wet and dry regions (because the respective absolute amounts might significantly differ form each other). Comparing the seasonal fields for the reference (past) and for the future over Hungary (not shown), one can conclude, that the basic spatial distribution of the precipitation field will remain unchanged: the minimum values can be found over the Great Hungarian Plain, and the precipitation amount is increasing towards the northern and western parts of the country. The decrease in spring is valid for the entire country, however, the most significant one will be over the area between the Danube and Tisza rivers, where the seasonal mean is approximately 55–60 mm/month in the reference, and the more than 10% decrease results in 50–55 mm/month for the future. In summer when the precipitation amount is higher than in spring, besides the general reduction some increase can be expected over the northern (elevated) regions – here the precipitation is enhanced to around 80–100 mm/month in average. The autumn tendencies are rather interesting: over the western part of Hungary increase is foreseen, whereas in the East precipitation decrease can be expected, all this results in the slight average enhancement (3%) as mentioned above and can be read from *Table 3*. This spatial distribution is a very crucial issue, because these tendencies might have even dramatic consequences: namely the reduction will be realized over an area where the rainfall is anyway occasionally missing (and it is the case also in summer and autumn over the southern part of Hungary), therefore, the number of drought events might increase in the future. In winter the 0–10% precipitation increase means around 5 mm/month extra precipitation almost everywhere in the domain (most probably considering the simultaneous change of temperature, this precipitation would fall in the form of rain).

4. Summary, conclusions, discussion, and future plans

In this article an overview was given about the validation of the REMO regional climate model and about the main characteristics of the expected climate change over Hungary based on the transient simulation of the model. According to former results of large international cooperations, the regional climate models in general and REMO in particular have a characteristic feature in the summer and autumn months over the Danube catchment area: namely it predicts too warm and dry climate for that region.

The main motivation for the validation of the REMO5.0 simulation was on the one hand, to explore the weaknesses and strengths of the model over Hungary for a longer past period, and on the other hand, to check whether the summer drying problem also appears in the model version adapted in 2004 at the Hungarian Meteorological Service. A long transient climate change simulation was carried out for the hundred-year period of 1951–2050. The model domain covers almost the entire continental Europe with 0.22 degree horizontal and 20 levels vertical resolution, and the lateral boundary forcings were provided by the ECHAM5/MPI-OM coupled atmosphere-ocean model system. For the future part of the integration, the A1B SRES scenario was applied for the global model in order to describe the greenhouse gas and aerosol emissions.

Generally it can be said (based on the subjective and objective verifications achieved for the time being), that the results just partly confirm the conclusions of the former studies: although the REMO model indeed overestimates the temperature over the southeastern part of the continent, over the other parts of the Danube catchment and particularly in Hungary its temperature prediction is quite reliable not only annually, but seasonally as well; furthermore, the precipitation patterns are mostly characterized by overestimation: the underestimation is restricted to the Adriatic coasts, whereas over the rest of the domain (including also Hungary) the overestimation is typical. Consequently, one can simply say that the model simulation for the recent past is cooler and more humid than it was anticipated based on earlier results.

Nevertheless, the temperature differences between the simulated and observed fields are quite convincing and encouraging from the point of view, that the REMO5.0 will provide realistic temperature projections also for the future. However, it has to be mentioned that even perfect past simulation does not guarantee that the future projection will be equally perfect (and the reverse is also true – maybe in lesser extent –, i.e., erroneous past simulation is not surely accompanied by wrong climate projection). Nevertheless, it is believed that the *real* model developments (based on the understanding and improvement of the inaccurately described physical processes) can essentially contribute to the enhancements of the regional climate models. In the case of precipitation the results proved to be too humid over the major part of the continent, however, in Hungary the magnitude of the errors is much lower reaching a rather satisfactory level. This humid characteristic can be caught not only in the context of the differences between model results and observations, but also in the inter-comparison of the global and regional fields: REMO5.0 simulates a moister past climate than it was originally in the forcing ECHAM-fields. It is especially noticeable over the highly elevated parts of Europe (like the Alps, the Carpathians, the Dinaric Alps) and it is believed as a straight consequence of the finer horizontal resolution of the regional model. (The resolution ratio between the two models is not even negligible: the REMO5.0 has approximately 8.5 times finer resolution than it is the case for ECHAM5/MPI-OM.) Furthermore, the regional model gives unrealistically high precipitation in the vicinity of the northern boundary. This feature is not unknown for regional climate models, where spurious precipitation patterns appear near to the model boundaries. These phenomena are usually explained by the inconsistency between the RCM's internal circulation and the lateral boundary forcings. It might be still the case for REMO in spite of the fact that the physical parameterization packages of the RCM and the GCM are quite similar. One possibility to check whether the strange features are really caused by this incompatibility and reduce it would be the application of two-way nesting technique (*Lorenz* and *Jacob*, 2008), when not only the large scale processes constraint the regional model, but also the small scale processes supply feedback to the global model through more realistic two-way lateral boundary interactions. Besides implementing the global and regional models at the same location, the only disadvantage of the method is its enormous computer resources, because it requires the simultaneous execution of the regional and global models with continuous interactions between them (and this constraint makes impossible to apply the method at the Hungarian Meteorological Service).

As far as the climate change part of the simulation is concerned, it can be pinpointed with rather large confidence, that by the middle of the 21st century, the mean temperature over Hungary will increase with about 1–2 °C in every season, with the smallest values (1.1 °C) in spring and largest ones (1.6 °C) in autumn. These outcomes are in good agreement with the results of the other regional climate model (the ALADIN-Climate model, *Csima*, 2008) adapted at the Hungarian Meteorological Service. The precipitation changes can not be specified so unambiguously: the annual change is a non-significant decrease with around 1 (!) percent, but among the seasons large differences can be experienced. In the first half of the year, i.e., in spring and summer, some reduction can be expected (with larger relative percentage in spring), then it is followed by precipitation increase in autumn and especially in winter. The precipitation surplus in autumn is valid only in spatial average, the details indicate, that over the western part of Hungary some increase, whereas over the eastern (anyway dryer) side of the country rather some decrease is anticipated. This latter fact might induce, that the drought and extremely dry years in the East might mean serious threats for the agriculture. For any case, it is mentioned here that one has to be careful, while interpreting such regional details, because the 25 km resolution of REMO is still on the limit for making such conclusions possible (certainly it would be desirable in the future to realize higher resolution experiments to check the aforementioned regional details). On the other hand, the simulation for the past indicated that the REMO model is capable for providing small scale details for instance for the wind speed, where the most important climatological wind characteristics of Hungary were successfully reflected by the model (not shown).

Basically, all these findings are more or less in good consistency with the tendencies obtained in the PRUDENCE project, which justifies the higher level of temperature change in Hungary than the global average as well as the similar intra-annual distribution of future precipitation (*Christensen*, 2005). (It is strongly emphasized here that these are certainly very qualitative statements due to the fact that the PRUDENCE experimentations were preformed with different SRES scenarios, and moreover, with different lateral boundary forcings in certain cases and for a time slice over the very end of the 21st century.) Besides the concrete projections, another main conclusion of the PRUDENCE project was that Central and Eastern Europe is a very “uncertain” region from the modeling point of view, because the simulations based on different regional climate models result in quite deviating projections (especially for temporal distribution of precipitation). More particularly, Hungary is situated in an “intermediate” zone, between the northern regions anticipated more humid in the future and the southern ones expected drier in the future (this also calls for more regional simulations with different RCMs for our region of interest).

Finally, it has to be remarked that the results introduced in this article are still preliminary ones and they are based only on one (the REMO) model. It provides very useful hints for applicability of the model for the Carpathian Basin, and moreover, also gives high resolution estimations for the future climate change over the region, which are the first such realizations in Hungary. Nevertheless, in order to draw more reliable and robust conclusions on the one hand, even more sophisticated analysis of the results are necessary, and on the other hand, comparisons to other models' results are indispensable in order to objectively quantify the uncertainties in the projections. For that purpose the results of ALADIN-Climate model (for the time slice of 2021–2050) with the use of the same A1B scenario in the framework of the CECILIA project (Central and Eastern Europe Climate Change Impact and Vulnerability Assessment, http://www.cecilia-eu.org) are going to provide a good basis at the Hungarian Meteorological Service, and the RCMs adapted at the Eötvös Loránd University (PRECIS and RegCM models) will provide further comparable projections, too.

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Adaptation of the RegCM3 climate model for the Carpathian Basin

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Abstract—Sensitivity experiments of present day climate (1961–1970) using the well-known regional climate model RegCM3 are analyzed over a complex topography domain covering the Carpathian Basin and its surroundings. The horizontal resolution of the model experiments is 10 km, the highest so far used with the RegCM modeling framework. When RegCM3 is run with the original settings used for coarser resolutions, highly unrealistic precipitation values are found in the selected domain, namely a large overprediction of precipitation. In order to reduce this large precipitation bias, we adjusted some of the parameters in the precipitation parameterization and compared results with the original model set up. Annual and seasonal average temperature and precipitation over different sub-regions of the domain are intercompared across the model versions and compared to observational datasets. The results show that the performance of the modified model is considerably better for the Carpathian Basin, especially for annual and seasonal precipitation, which show small biases with the new parameter setting. Our study indicates that some model parameters may have to be suitably modified to use the RegCM at very high resolutions.

Key-words: regional climate model, temperature, precipitation, Carpathian Basin, model validation

1. Introduction

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (*IPCC*, 2007) suggests changes in regional climate conditions in the 21st century, such as increasing winter precipitation and decreasing summer precipitation over Central Europe. Moreover, studies with different greenhouse gas emission scenarios show that Europe is one of the Earth's most sensitive regions to global warming (*Giorgi*, 2006). These results are obtained using global climate models (GCM), which are typically run at low spatial resolutions (200–300 km). The main goal of the global model simulations is to capture the effects of large scale processes on the climate system, including land-ocean-atmosphere and sometimes biosphere feedbacks.

One technique that can be use to obtain finer scale climate change information at the regional scale is the use of nested regional climate models (RCM) (*Giorgi* and *Mearns*, 1999). RCMs can focus on specific regions using fine spatial resolutions of the order of 10–50 km, and they are run using as initial and lateral boundary conditions the output from GCM simulations. In the frame of the PRUDENCE project (European Union 5th Framework Program), several RCM simulations of present day (1961–1990) and future (2071–2100) climate were carried out for the entire European continent using 50 km horizontal resolution (*Christensen*, 2005). Based on the 1961–1990 reference period, both the simulated temperature and precipitation values in the PRUDENCE models exhibited substantial biases over the Carpathian Basin, particularly in summer, when they exceeded 2.5 °C and 25%, respectively (*Jacob et al.*, 2007).

As part of the project CECILIA (Central and Eastern Europe Climate Change Impact and Vulnerability Assessment; *Halenka*, 2007) we plan to use the regional climate model RegCM3 originally developed by *Giorgi et al.* (1993a,b) and further modified as described by *Pal et al.* (2007) to produce climate change scenarios over Hungary and the surrounding regions at very high resolution, 10 km. This is to date the highest resolution used within the RegCM3 model framework, and therefore, an important first step in the project is the evaluation of the model performance at this resolution. We here present preliminary results from such an analysis.

We carried out two sets of 10-year simulations with the model over a domain covering our region of interest. First, the standard model set up was adopted, which has been mostly used for resolutions of the order of 30–50 km. After the results from this run showed significant biases in the model simulation, we modified some model parameters to improve the model biases and repeated the simulation. These changes are justified by the fact that 10 km is a resolution at which the assumption underlying standard physics schemes (e.g., convection) may be expected to loose validity, and thus the model may need to be recalibrated. Both simulations are driven at the lateral boundaries by analyses of observations. In this paper we intercompare the two simulations and discuss the model sensitivity to these parameter changes, with a focus on seasonal and annual temperature and precipitation. In the next section we begin with a description of the model and experiment design.

2. *Model description and experiment design*

2.1. Description of RegCM

In order to simulate the climate of the Carpathian Basin, the latest version of RegCM (RegCM3) and a modified version of RegCM3 are used for the reference period 1961–1990. This model was originally developed by *Giorgi et al.* (1993a,b), and then modified, improved and discussed by *Giorgi* and *Mearns* (1999), *Giorgi et al.* (2003), and *Pal et al.* (2007). The dynamical core of the RegCM3 is fundamentally equivalent to the hydrostatic version of the National Center for Atmospheric Research (NCAR) and the Pennsylvania State University joint mesoscale model MM5 (*Grell et al.,* 1994). Surface processes are represented in the model via the Biosphere-Atmosphere Transfer Scheme, BATS (*Dickinson et al.,* 1993). The non-local vertical diffusion scheme of *Holtslag et al.* (1990) is used to calculate the boundary layer physics. Additionally, the physics parameterization is mostly based on the comprehensive radiative transfer package of the NCAR Community Climate Model, the latest version CCM3 (*Kiehl et al.,* 1996). Fraction of cloud ice is diagnosed by the scheme as a function of temperature, and solar radiative transfer is calculated with δ–Eddington approach (*Lenoble*, 1993). The cloud radiation is calculated in a function of cloud fractional cover, cloud effective droplet radius, and cloud liquid water content. The mass flux cumulus cloud scheme of *Grell* (1993) is used to represent the convective precipitation with two closures as an option: *Arakawa* and *Schubert* (1974) and *Fritsch* and *Chappell* (1980). The resolvable scale precipitation is represented via the scheme of *Pal et al.* (2000). This scheme includes a prognostic equation for cloud water and allows determining the subgrid-scale variability of clouds.

2.2. RegCM experiments for the Carpathian Basin

All RCM experiments are initialized on January 1, 1960 and integrated until December 31, 1970, the first year (1960) serves as the spin-up period of the model. The model domain covers 120 × 100 grid points at 10 km grid spacing and centered over Hungary (*Fig. 1*). The domain includes the Carpathian Basin and surrounding areas. The main topographical features of the domain, such as the Carpathians enclosing the basin in the east, the Alps to the west, the Dinari mountains to the south, and a small fraction of the Adriatic sea are also represented.

The topography of the terrain is quite complex, especially at the boundaries, which can cause significant fine-scale variations in weather and climate. The RegCM can be run with initial and lateral boundary conditions (ICBC) from global analysis datasets, the output of a GCM or the output of a previous RegCM simulation. In our experiments the ICBCs are interpolated at

6-hourly intervals from the 45-year reanalysis datasets (ERA-40) of the European Centre for Medium-Range Weather Forecasts (ECMWF). We carefully selected the appropriate setting through various sensitivity experiments, for instance, we changed the number of vertical levels (14, 18, and 23). Although the ECMWF's numerical weather forecast model applies 91 vertical levels (*ECMWF*, 2007), this is not the case in the regional climate models, where usually only 15–30 vertical levels are used (e.g., *Jacob et al.,* 2007). Furthermore, we made test runs with different convective schemes, different type of lateral boundary conditions (sponge, linear, and exponential), and different resolutions (with and without double nesting), and the settings for the 30-year experiments have been selected on the base of the preliminary results of these test runs. Since we are specifically interested in precipitation and temperature in high spatial resolution to validate present-day climate simulation, we used the gridded climatological data provided by the Climatic Research Unit (CRU) of the University of East Anglia (CRU TS 1.2 dataset; *Mitchell* and *Jones,* 2005) for the comparisons.

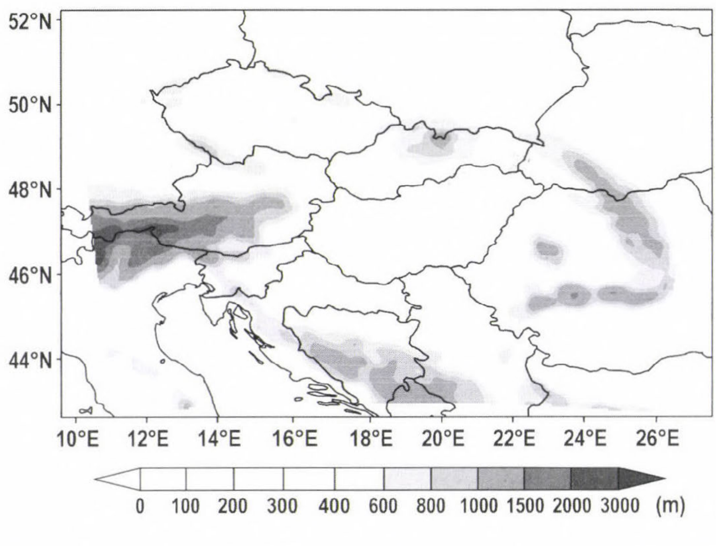

Fig. 1. Model domain and topography (m) for the simulations (10 km grid spacing).

2.3. Adjustment of RegCM parameters

As discussed below, the standard verison of RegCM3 substantially overestimated precipitation over the whole domain, except for the southeastern part of the Alps. In order to decrease precipitation the following parameters were changed: the cloud-to-rain autoconversion rate was decreased from 0.0005 to 0.00025, the raindrop evaporation rate coefficient was increased from $0.2 \cdot 10^{-4}$

to $1.0 \cdot 10^{-3}$ (kg m^{-2} s^{-1})$^{-1/2}$ s^{-1}, the raindrop accretion rate was decreased from 6 to 3 m^3 kg s. Note that all these parameters appear in the resolvable scale precipitation scheme (see *Pal et al.,* 2000), they are all quite uncertain, and these changes made agree within bounds found in the literature. This choice was made because at 10 km resolution most precipitation was produced by this scheme even in the summer, probably because the Grell convection scheme is not activated often at high resolution. The final settings of the parameter are based on expert judgement of the model developers (with almost two decades of modeling experience) and several test runs of RegCM3 for the Carpathian Basin. Of course, the ideal optimization process of model parameters would be based on statistical techniques (e.g., Monte-Carlo simulation, Bayes' theorem), however, due to computational constraints it is not possible to fully accomplish this type of calibration process in case of regional climate models. We call the version of RegCM3 with the above listed changes as RegCM Beta. Details of the RegCM3 and RegCM Beta experiments are summarized in *Table 1*. In both simulations the model employs 18 vertical σ–levels reaching up to 70 hPa with time step 30s and the Grell cumulus scheme with the Fritsch-Chappell closure (see *Grell*, 1993).

Table 1. Settings of the simulations including the modified values of the parameterizations

	RegCM3	**RegCM Beta**
Driving field	ERA-40	ERA-40
Number of grid points	120 × 100	120 × 100
Number of vertical levels	18	18
Spin-up	1 year	1 year
Integration time	Jan 01, 1961–Dec 31, 1970	Jan 01, 1961–Dec 31, 1970
Time step	90 s	90 s
Cloud-to-rain autoconversion rate	0.0005	0.0025
Raindrop evaporation rate coefficient	$0.2 \cdot 10^{-4}$ (kg m^{-2} s^{-1})$^{-1/2}$ s^{-1}	$1.0 \cdot 10^{-3}$ (kg m^{-2} s^{-1})$^{-1/2}$ s^{-1}
Raindrop accretion rate	6 m^3 kg s	3 m^3 kg s

3. Results

In this section the results of the 10-year long simulations (1961–1970) are presented and discussed. The results are shown on a smaller fraction of the entire model domain after eliminating the buffer zone (*Fig. 1*). In order to analyze the model performance in simulating temperature and precipitation, spatial averages are calculated. When computing these spatial averages the buffer zone, which consists of 12 grid points in each direction, is neglected. Since in earlier studies (*Bartholy et al.*, 2006) a large overestimation of precipitation and underestimation of temperature were found in summer, for the standard RegCM, special consideration is given to the summer results. The bias fields presented in the maps are defined as the difference between the simulated (RegCM3 or RegCM Beta) and observed (CRU) datasets. The mean bias value is defined as the spatial average of these differences.

3.1. Temperature

Fig. 2 compares the annual mean 2-meter air temperatures in RegCM3 and RegCM Beta with the CRU data and the driving ERA-40 data. The maps of *Fig. 2* present the annual average of the RegCM data (lower panels), average of CRU data (upper right panel), and average of ERA-40 data (upper left panel). The bias fields between the RegCM and CRU data are presented in *Fig. 3*. The CRU temperature field shows substantial spatial variability with topographically induced fine-scale regional features. The topographic signal related to the mountain chains of the Carpathians and the eastern edge of the Alps is evident in each seasonal and monthly average as well. (The region of the Adriatic Sea is white in all CRU maps due to the fact that CRU data are available only over land).

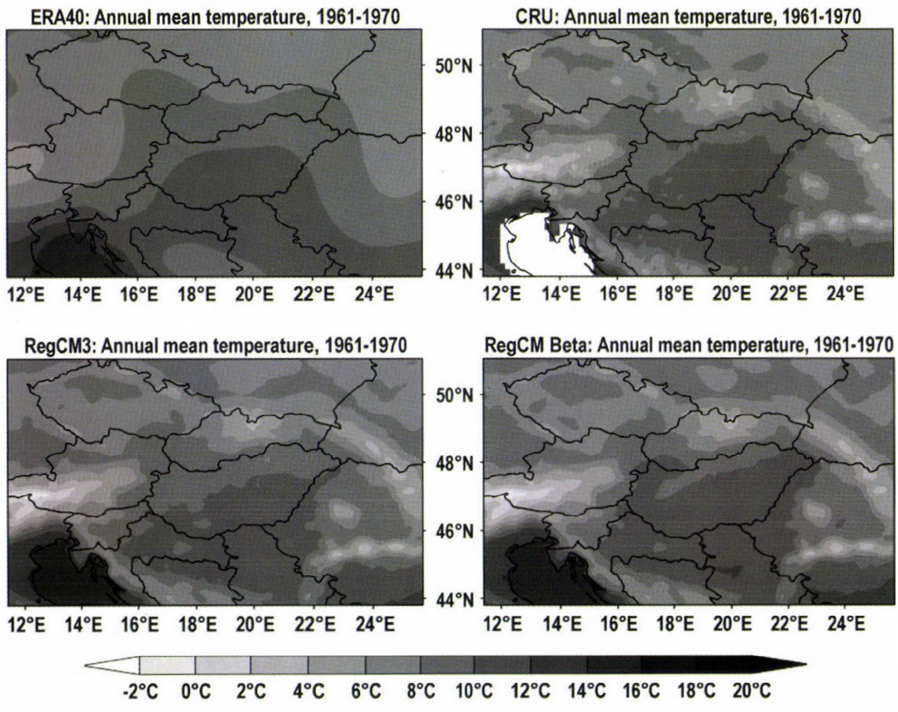

Fig. 2. Spatial distribution of mean annual 2-meter air temperature (°C) averaged over the period 1961–1970. The lower maps corresponds to the result for RegCM3 and RegCM Beta, the upper right map is the annual mean temperature calculated from CRU TS 1.2, and the upper left map is the annual mean temperature calculated from driving data (ERA-40).

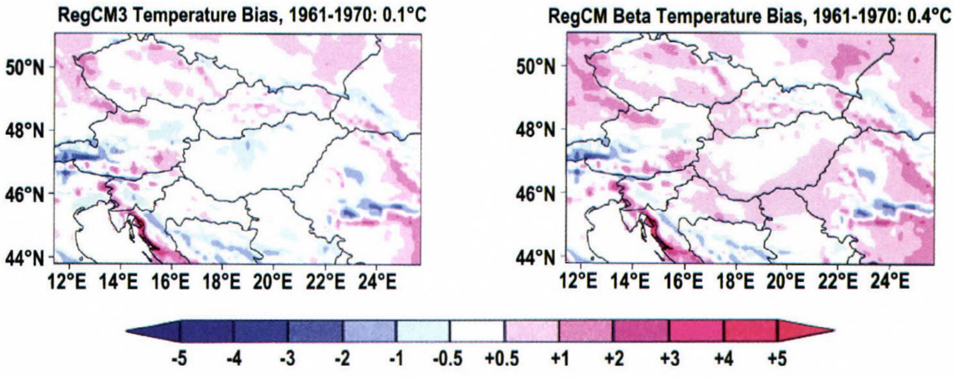

Fig. 3. Spatial distribution of the mean temperature bias (RegCM-CRU, in °C) of RegCM3 and RegCM Beta. The annual average bias field is calculated for the period 1961–1970.

The annual averaged RegCM (both RegCM3 and RegCM Beta) results are very similar to the CRU data. It is clearly shown in *Fig. 2* that the 2-meter air temperature in the annual average is well captured by the regional model (the results were improved a lot compared to the ERA-40 fields), especially, over lowlands. Focusing on Hungary, a very moderate cold bias occurred over the mountainous subregion in the case of the RegCM3 simulation (*Fig. 3*). Complex topography of a domain – such as the surrounding region of Hungary – is always difficult to reproduce for climate models at high resolution (e.g., 10 km) (*Halenka et al.,* 2006). Both simulations show a small warm bias (0.08 °C and 0.36 °C) for the entire domain, the spatially averaged warm bias of the RegCM Beta simulation is a bit higher than the one of the standard RegCM3. The spatial distribution of the bias is very similar in the two simulations. The annual average temperature bias over Hungary is –0.1 °C and 0.45 °C in case of RegCM3 and RegCM Beta, respectively (*Fig. 4*).

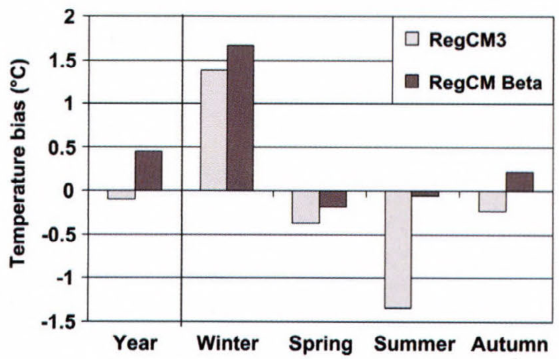

Fig. 4. Annual and seasonal spatial average 2-meter air temperature bias (°C) of RegCM3 and RegCM Beta over Hungary.

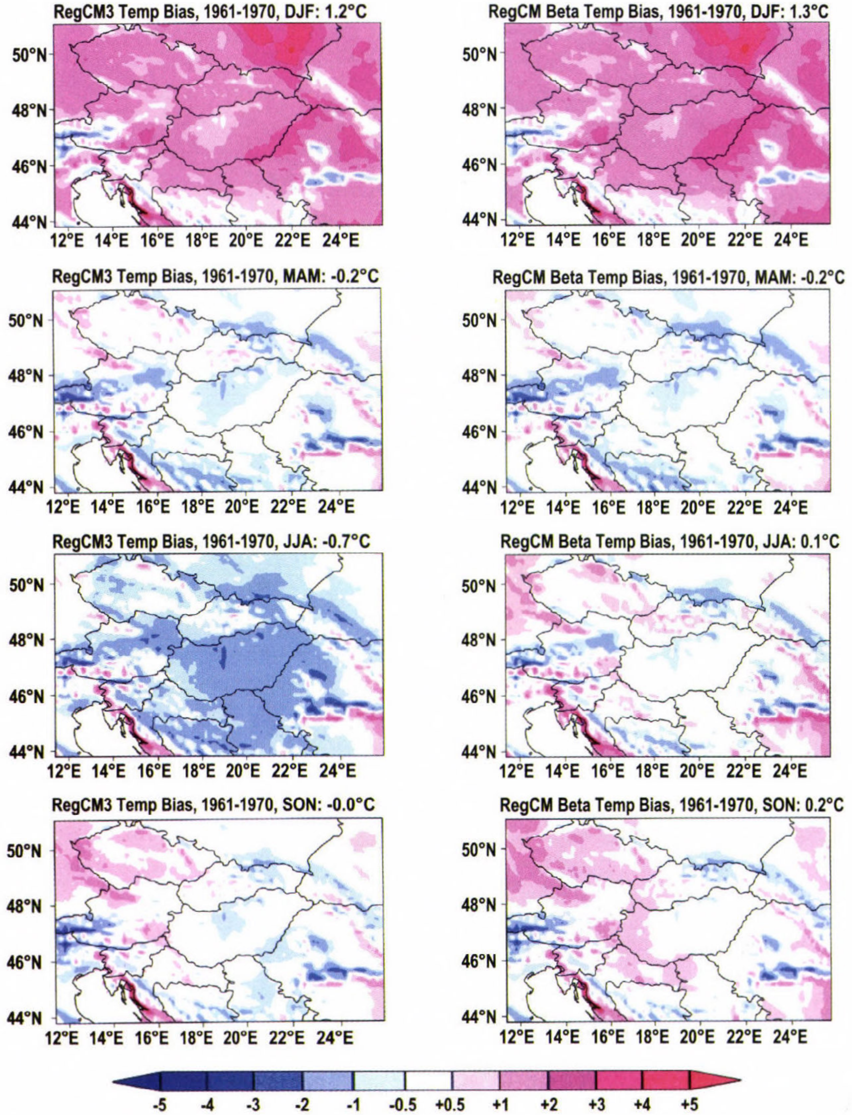

Fig. 5. Spatial distribution of seasonal bias (RegCM-CRU) of 2 meter air temperature (°C) averaged over the period 1961–1970. Maps on the left and on the right represent the RegCM3 and RegCM Beta bias fields, respectively.

The seasonal temperature bias fields are shown in *Fig. 5*. In the transitional seasons, both bias values are relatively small in the entire region (the spatial average is not exceeding 0.23 °C in absolute value) and in Hungary (the spatial average bias is less than 0.37 °C in absolute value), and the results from the RegCM3 and RegCM Beta simulations provide similar structure of the bias fields. During the summers of 1961–1970 some substantial differences between RegCM3 and RegCM Beta simulated surface air temperature are found. In particular, the RegCM3 results show a dominant cold bias over Hungary (–1.34 °C on spatial average as shown in *Fig. 4*), while in case of the RegCM Beta results the bias does not exceed 0.05 °C in absolute value. This means that only the RegCM Beta simulations reproduced the hottest summer temperature over the Hungarian Great Plains. The largest bias values are found in winter for both simulations, with no improvement found in the RegCM Beta version. The spatial structures of the bias fields are similar, the spatially averaged bias values are 1.22 °C (RegCM3) and 1.32 °C (RegCM Beta) for the entire domain, and 1.38 °C (RegCM3) and 1.67 °C (RegCM Beta) for Hungary (*Fig. 4*).

Summarizing the above results, a cold bias is found in the RegCM3 simulations except in winter, while a small warm bias is found in the RegCM Beta simulation except in spring. *Fig. 5* indicates that RegCM Beta model runs simulate temperature more realistically in summer over the entire domain than RegCM3. Overall, the results of both simulations agree well with the spatial patterns of the annual surface air temperature of the CRU observations. On the basis of the simulated 10 years, the modification made in RegCM3 to RegCM Beta lead to a significant improvement of 2 meter air temperature simulations in summer. This conclusion is also supported by the RMSE values shown in *Table 2* (first two columns).

Table 2. Root mean square error (RMSE) for temperature and for precipitation

RMSE	Temperature (°C)		Precipitation (mm/day)	
	RegCM3	RegCM Beta	RegCM3	RegCM Beta
Winter (DJF)	1.3	1.4	1.2	0.6
Spring (MAM)	0.5	0.5	2.0	0.6
Summer (JJA)	0.9	0.5	2.9	0.6
Autumn (SON)	0.5	0.5	1.0	0.4
Year	0.5	0.6	1.8	0.5

3.2. Precipitation

In this section the precipitation results of RegCM3 and RegCM Beta are discussed and compared to CRU data with a similar approach as in the case of temperature (section 3.1). *Fig. 6* shows the annual mean precipitation; results of the RegCM3 and RegCM Beta can be seen on the left and on the right, respectively. In the case of RegCM3 the bias map is dominated by a dark green color, which means large overestimation of precipitation over the whole domain. The precipitation bias of RegCM3 simulations exceeds 85% on average. This bias is significantly reduced using RegCM Beta to 15%, especially in lowland areas (e.g., in Hungary from 84% to 26%, as shown in *Fig. 7*). The largest bias occurs over the mountainous subregions in both simulations. The only region where RegCM3 shows lower biases for precipitation is the southeastern edge of the Alps, but this can be attributed to the special effect of this region on precipitation in regional climate simulations.

The annual and seasonal RMSE values of precipitation amounts are shown in *Table 2* (last two columns). As these values suggest, the RegCM Beta simulations resulted in significantly smaller error values, in case of the annual precipitation the RMSE decreased by 73%, while in case of the seasonal precipitation the RMSE decreased by 46%, 71%, 78%, and 58% in winter, spring, summer, and autumn, respectively.

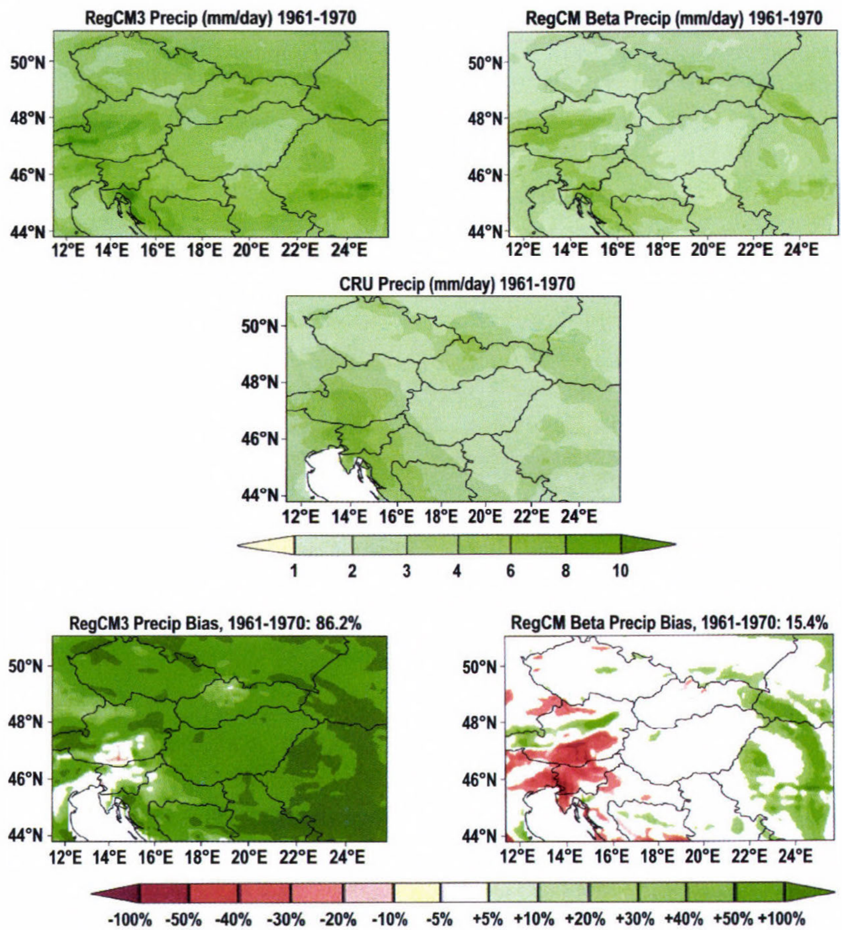

Fig. 6. Spatial distribution of precipitation (mm/day) averaged over the period 1961–1970. The upper maps correspond to the result for RegCM3 and RegCM Beta, the middle map is the annual mean precipitation calculated from CRU TS 1.2, and the lower maps are the bias fields (RegCM-CRU, in %) of RegCM3 and RegCM Beta.

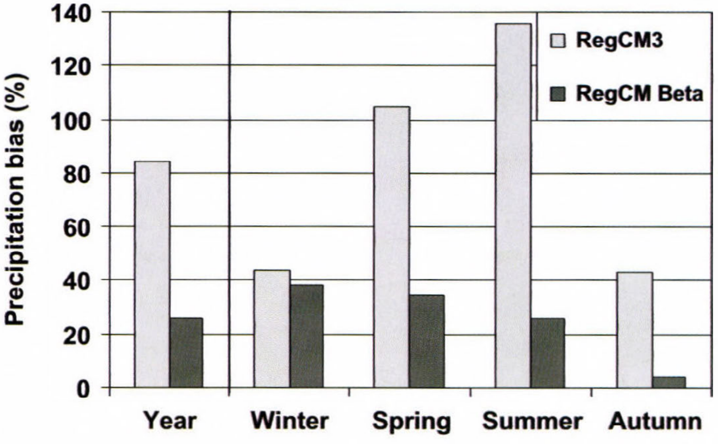

Fig. 7. Annual and seasonal spatial average precipitation bias of RegCM3 and RegCM Beta over Hungary.

Seasonal precipitation bias fields for the 1961–1970 period are shown in *Fig. 8*. Maps on the left represent the spatial structure of the seasonal bias in case of the RegCM3 simulation. These maps are dominated by a large overestimation in the entire domain in all seasons: the bias is 82% in winter, 98% in spring, 108% in summer, and 65% in autumn. For Hungary, these bias values are 44% in winter, 105% in spring, 135% in summer, and 43% in autumn (*Fig. 7*). As a result of the tuning the physical parameterizations in RegCM Beta, the seasonal bias values are reduced significantly, not exceed 47% for seasonal averages over the entire domain (maps shown on the right of *Fig. 8*). The spatial averages of seasonal bias are 47% in winter (38% for Hungary), 26% in spring (35% for Hungary), 7% in summer (26% for Hungary), and –2% in autumn (4% for Hungary).

During summer (JJA) RegCM3 simulates heavy rainfalls over mountainous subregions except in the southeastern edge of the Alps. RegCM3 could not represent well the minimum and maximum rainfall; additional heavy rainfall covers several smaller areas over the southern part of the domain. Observed rainfall was concentrated over high altitudes (Alps and Carpathians), where maximum values of precipitation were about 5 mm/day, but the maximum values of RegCM3 exceeded 10 mm/day. Although in case of the RegCM Beta simulation the precipitation is less intense, and the overall structure and the magnitude of precipitation pattern are reproduced quite well, the mean precipitation fields differ from the CRU datasets in some respects. The simulated precipitation is less than the observed over the southeastern parts of the Alps and over the northern part of Slovakia (mountain Tatra). However, there may exist some uncertainty in observational precipitation data over these high mountains.

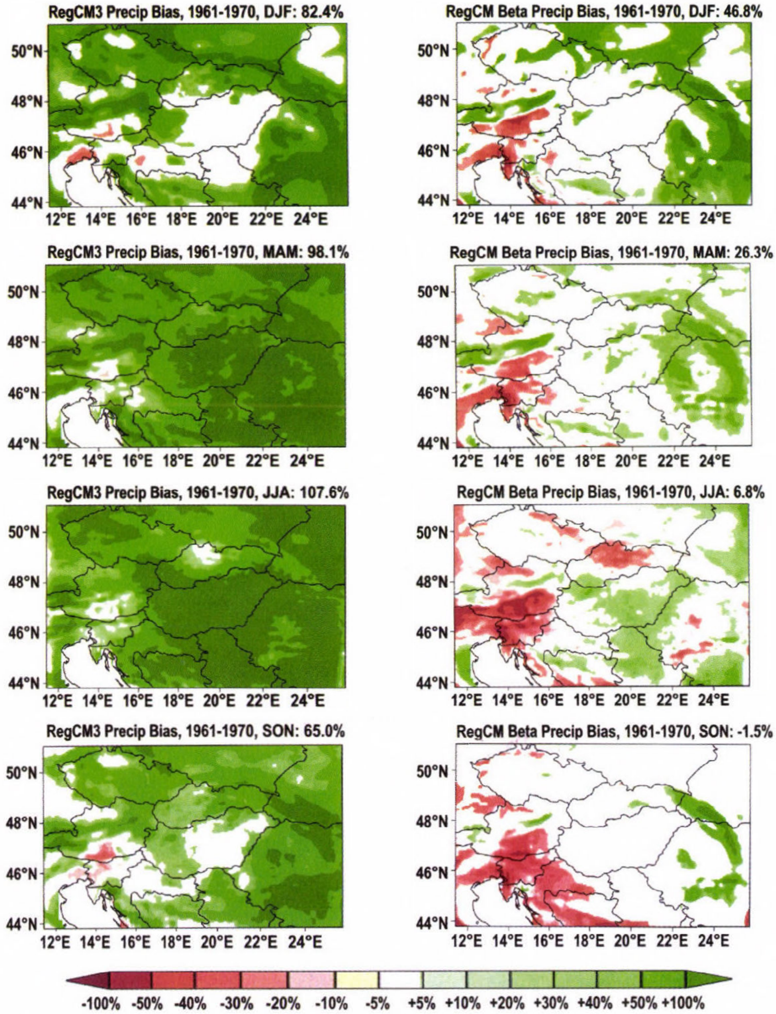

Fig. 8. Spatial distribution of seasonal precipitation bias (RegCM-CRU, in %) averaged over the period 1961–1970. Maps on the left and on the right represent the RegCM3 and RegCM Beta bias fields, respectively.

Summarizing the above results, RegCM3 produced unrealistic precipitation results, with a positive bias exceeding 60% in all season over the entire domain. RegCM Beta simulated the precipitation far more realistically. Thus, the bias was reduced considerably, especially in summer, when the convective parameterization plays an important role in simulating precipitation. Not only the precipitation pattern but also the values themselves agree with the CRU data much more when using RegCM Beta. Although the modifications made to the RegCM3 yield considerably drier simulations, an overestimation of precipitation still exists in some parts of the domain, especially in mountainous regions.

In order to illustrate the ratio of the stratiform and convective precipitation, *Fig. 9* presents an example for June. The maps suggest that both types are considerably reduced to more realistic values in case of RegCM Beta.

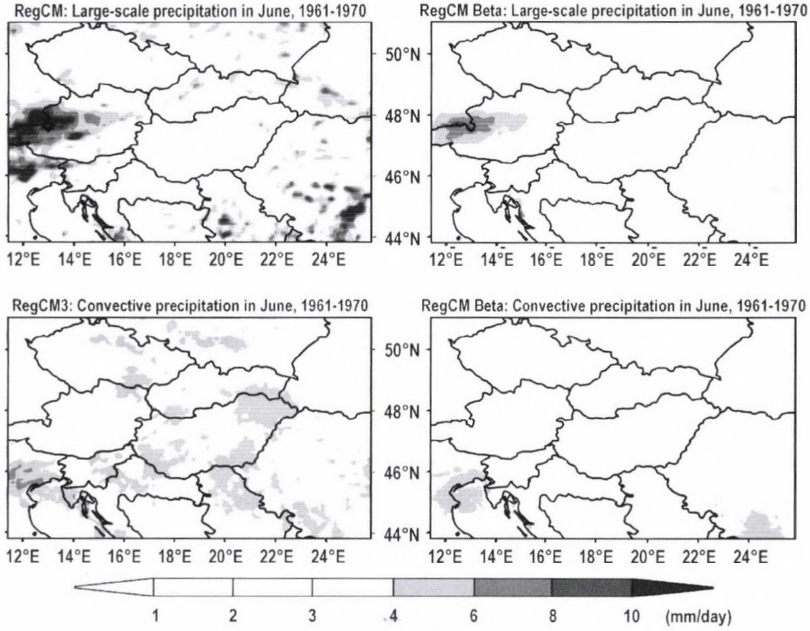

Fig. 9. Monthly mean stratiform (upper maps) and convective (lower maps) precipitation in June, 1961–1970. Maps on the left and on the right represent the RegCM3 and RegCM Beta simulated values, respectively.

4. Conclusions

The regional climate model RegCM3 has been adapted for high resolution simulations over a Central European domain centered around Hungary. The horizontal resolution of the model is 10 km, and decade-long (1961–1970) simulations have been conducted and analyzed. When the original settings of RegCM3 are used, the simulated precipitation pronouncedly exceeds the observed seasonal and annual values, especially in summer and spring. These standard settings have been used for resolutions of 25–50 km and appear not to work properly at resolutions of about 10 km. It is important to note that at the resolution of 10 km the scale separation assumption, underlying the model convection scheme and its interaction with the large scale precipitation scheme, may not be entirely valid. Therefore, a few parameters in the precipitation parameterization scheme were adjusted, namely the cloud-to-rain autoconversion rate, the raindrop evaporation rate, and the raindrop accretion rate, with the aim of reducing precipitation. This modification of physical parameters resulted in a significant improvement of the precipitation simulation. The overestimation in seasonal precipitation was much reduced, 47% in winter, 26% in spring, 7% in summer, and –2% in autumn for the entire domain. For Hungary, the large positive bias of the summer and spring precipitation found in the standarad RegCM were reduced to 26% and 7%, respectively, leading to a good precipitation simulation. According to these results, the performance of the modified model is considerably better over the entire domain, and especially for Hungary, in the case of precipitation. In case of temperature the positive winter bias (exceeding 1 °C) was not improved in the RegCM Beta version, but the large cold bias of summer temperature was reduced significantly, likely because of the reduced precipitation amounts. In the transition seasons both model experiments reproduced the observational temperature values well with less than 0.5 °C bias.

Our results show that the RegCM simulated precipitation exhibits a substantial sensitivity to horizontal resolution, thus confirming the previous findings of *Giorgi* and *Marinucci* (1996). We stress that the 10 km scale is at the limits of the applicability of cumulus convection schemes, so that the poor performance of the standard RegCM model is not surprising. In particular, we found that at 10 km the Grell convection scheme is not sufficiently activated, so that much of the summer precipitation is produced by the large scale scheme. For this reason, in the RegCM Beta version the parameter adjustment was carried out on the resolvable scale parameterization.

After this adjustment, the RegCM Beta version shows a good performance over the region even at the 10 km resolution and thus, it can be used to simulate future climate conditions (e.g., 2021–2050 and 2071–2100) using the output of coarse resolution GCMs as lateral boundary conditions. These simulations are currently under way in the frame of the CECILIA project and will be reported on in future papers.

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Analysis of expected climate change in the Carpathian Basin using the PRUDENCE results

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Abstract—Expected temperature and precipitation changes are analyzed for the Carpathian Basin and, especially, in Hungary, for the 2071-2100 period using outputs of the PRUDENCE project for the A2 and B2 emission scenarios. Different regional climate models (RCMs) of PRUDENCE use 50 km as horizontal spatial resolution, which enables us to estimate the climate change on regional scale. Composite maps of the expected seasonal temperature change and trend analysis of extreme temperature indices suggest that a regional warming trend is evident in the Carpathian Basin. According to the results the largest warming is expected in summer. Negative temperature extremes are projected to decrease while positive extremes tend to increase significantly. The climate simulation results suggest that the expected change of annual total precipitation is not significant in the Carpathian Basin. However, significantly large and opposite trends are expected in different seasons. Seasonal precipitation amount is very likely to increase in winter, and it is expected to decrease in summer, which implies that the annual distribution of precipitation is expected to be restructured. The wettest summer season may become the driest (especially in case of A2 scenario), and the driest winter is expected to be the wettest by the end of the 21st century. The extreme precipitation events are expected to become more intense and more frequent in winter, while a general decrease of extreme precipitation indices is expected in summer.

Key-words: regional climate model, temperature, precipitation, Carpathian Basin, extreme climate index, expected trend

1. Introduction

Spatial resolution of global climate models (GCMs) is inappropriate to describe regional climate processes; therefore, GCM outputs may be misleading to compose regional climate change scenarios for the 21st century (*Mearns et al.,* 2001). In order to determine better estimations for regional climate parameters, fine resolution regional climate models (RCMs) can be used. RCMs are limited area models nested in GCMs, i.e., the initial and boundary conditions of RCMs are provided by the GCM outputs (*Giorgi*, 1990). Due to computational constrains, the domain of an RCM evidently does not cover the entire globe, and sometimes not even a continent. On the other hand, their horizontal resolution may as fine as 5–10 km. The first project completed in the frame of the European Union V Program is the PRUDENCE (Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects), which involved 21 European research institutes and universities. The primary objectives of PRUDENCE were to provide high resolution (50 km × 50 km) climate change scenarios for Europe for 2071–2100 using dynamical downscaling methods with RCMs (using the reference period 1961–1990), and to explore the uncertainty in these projections (*Christensen et al.*, 2007). Results of the project PRUDENCE are disseminated widely via Internet (http://prudence.dmi.dk) and several other media, and thus, they support socio-economic and policy related decisions.

In the frame of the project PRUDENCE, the following sources of climate uncertainty were studied (*Christensen*, 2005):

- Sampling uncertainty. Simulated climate is considered as an average over 30 years (2071–2100, reference period 1961–1990).
- Regional model uncertainty. RCMs use different techniques to discretize the differential equations and to represent physical processes on sub-grid scales.
- Emission uncertainty. RCM runs used two IPCC-SRES emission scenarios, namely, A2 and B2. 16 experiments from the PRUDENCE simulations considered the A2 scenario, while only 9 of them used the B2 scenario.
- Boundary uncertainty. RCMs were run with boundary conditions from different GCMs. Most of the PRUDENCE simulations used HadAM3H as the driving GCM. Only a few of them used ECHAM4 or ARPEGE (*Déqué et al.*, 2005).

In this paper, the regional climate change projections are summarized for the Carpathian Basin using the outputs of all available PRUDENCE simulations. Results of the expected mean temperature and precipitation change by the end of the 21st century are discussed using composite maps. Furthermore, the expected changes of the extreme climate indices following the guidelines suggested by one of the task groups of a joint WMO-CCl (World Meteorological Organization Commission for Climatology)/CLIVAR (a project of the World Climate Research Programme addressing Climate Variability and Predictability) Working Group formed in 1998 on climate change detection (*Karl et al.,* 1999; *Peterson et al.,* 2002) are also analyzed.

2. *Data*

Adaptation of RCMs with 10–25 km horizontal resolution is currently proceeding in Hungary, namely, at the Department of Meteorology, Eötvös Loránd University (*Bartholy et al.,* 2006), and at the Hungarian Meteorological Service (*Horányi*, 2006). Results of these RCM experiments are expected within 1–2 years, however, impact studies and end-users need and would like to have access to climate change scenario data much earlier. Also, for the Hungarian National Climate Change Strategy (accepted by the Parliament in March 2008), climate change input data are needed for Hungary. Therefore, in order to fulfill this instant demand with preliminary information, outputs of PRUDENCE simulations (for the 2071–2100 and 1961–1990 periods) are evaluated and offered for the Carpathian Basin. Composite maps of expected temperature and precipitation change cover the Carpathian Basin (45.25°–49.25°N, 13.75°–26.50°E). Since the project PRUDENCE used only two emission scenarios (i.e., A2 and B2), no other scenario is discussed in this paper. In case of the A2 scenario, 16 RCM experiments are used, while in case of B2, only outputs of 8 RCM simulations are available (*Table 1*).

Table 1. List of RCMs with their driving coupled GCMs used in the composite analysis

	Institute	RCM	Driving GCM	Scenario
1	Danish Meteorological Institute	HIRHAM	HadAM3H/HadCM3	A2, B2
2		HIRHAM	ECHAM4/OPYC	A2
3		HIRHAM high res.	HadAM3H/HadCM3	A2
4		HIRHAM extra high res.	HadAM3H/HadCM3	A2
5	Hadley Centre of the UK Met Office	HadRM3P (ensemble/1)	HadAM3P/HadCM3	A2, B2
6		HadRM3P (ensemble/2)	HadAM3P/HadCM3	A2
7	ETH (Eidgenössische Technische Hochschule)	CHRM	HadAM3H/HadCM3	A2
8	GKSS (Gesellschaft für Kernenergieverwertung in Schiffbau und Schiffahrt)	CLM	HadAM3H/HadCM3	A2
9		CLM improved	HadAM3H/HadCM3	A2
10	Max Planck Institute	REMO	HadAM3H/HadCM3	A2
11	Swedish Meteorological and Hydrological Inst.	RCAO	HadAM3H/HadCM3	A2, B2
12		RCAO	ECHAM4/OPYC	B2
13	UCM (Universidad Complutense Madrid)	PROMES	HadAM3H/HadCM3	A2, B2
14	International Centre for Theoretical Physics	RegCM	HadAM3H/HadCM3	A2, B2
15	Norwegian Meteorological Institute	HIRHAM	HadAM3H/HadCM3	A2
16	KNMI (Koninklijk Nederlands Meteorologisch Inst.)	RACMO	HadAM3H/HadCM3	A2
17	Météo-France	ARPEGE	HadAM3H/HadCM3	A2, B2
18		ARPEGE	ARPEGE/OPA	B2

According to the A2 global emission scenario, fertility patterns across regions converge very slowly resulting in continuously increasing world population. Economic development is primarily regionally oriented, per capita economic growth and technological changes are fragmented and slow. The projected CO_2 concentration may reach 850 ppm by the end of the 21st century (*IPCC*, 2007), which is about triple of the pre-industrial concentration level (280 ppm). The global emission scenario B2 describes a world with intermediate population and economic growth, emphasizing local solutions to economic, social, and environmental sustainability. According to the B2 scenario, the projected CO_2 concentration is likely to exceed 600 ppm (*IPCC*, 2007), which is somewhat larger than a double concentration level relative to the pre-industrial CO_2 conditions.

Regional analysis of the detected trend of different extreme climate indices for the Carpathian Basin is discussed by *Bartholy* and *Pongrácz* (2005, 2006, 2007), where the list and definition of the indices can be found also. In this paper, the expected future trends of extreme climate indices are analyzed in the Carpathian Basin using daily temperature and precipitation outputs of four different RCMs run by the (i) Danish Meteorological Institute (DMI), (ii) Abdus Salam International Centre for Theoretical Physics (ICTP) in Trieste, (iii) Royal Meteorological Institute of the Netherlands (Koninklijk Nederlands Meteorologisch Institute, KNMI), and (iv) Swiss Federal Institute of Technology Zurich (Eidgenössische Technische Hochschule Zürich, ETHZ). For all of these simulations the boundary conditions were provided by the HadAM3H/HadCM3 (*Rowell*, 2005) global climate model of the UK Met Office (Table 1). DMI used the HIRHAM4 RCM (*Christensen et al.,* 1996), which has been developed jointly by DMI and the Max-Planck Institute in Hamburg. ICTP used the regional climate model RegCM, which was originally developed by *Giorgi et al.* (1993a, 1993b) and then improved as described by *Giorgi et al.* (1999) and *Pal et al.* (2000). KNMI used the RACMO2 (*Lenderink et al.,* 2003), which combines dynamical core of the HIRLAM Numerical Weather Prediction System with the physical parameterization of the European Centre for Medium-range Weather Forecasting used for the ERA-40 re-analysis project. ETHZ used the Climate High Resolution Model (CHRM) RCM described by *Vidale et al.* (2003). Model performances of the four selected RCMs are analyzed by *Jacob et al.* (2007) using the simulations of the reference period 1961-1990. Besides the A2 scenario experiments, DMI and ICTP accomplished further experiments using the B2 emission scenario.

3. *Analysis of the expected regional climate change*

Composites of the mean seasonal temperature (daily mean, maximum, and minimum) and precipitation changes are mapped for both A2 and B2 scenarios. The spatial variation of the composite maps are summarized in tables for the gridpoints located inside Hungary. In order to represent the uncertainty of the composite maps, standard deviations of the RCM model results are also determined and mapped for all seasons.

First, the expected temperature change is discussed, followed by the analysis of the expected precipitation change for the Carpathian Basin.

3.1. Temperature

Fig. 1 presents the expected seasonal temperature change for A2 and B2 scenarios (left and right panel, respectively). Similarly to the global and the European climate change results, larger warming can be expected for A2 scenario in the Carpathian Basin than for B2 scenario. The largest temperature increase is expected in summer, while the smallest increase in spring. The same conclusion can be drawn from *Table 2*, where the intervals of the seasonal temperature increase are summarized for the area of Hungary. The largest warming is expected in summer for both scenarios: in case of the daily mean temperature the interval of the expected increase is 4.5–5.1°C (A2) and 3.7–4.2°C (B2), in case of the daily maximum temperature these intervals are 4.9–5.3°C (A2) and 4.0–4.4 (B2), and in case of the daily minimum temperature these intervals are 4.2–4.8°C (A2) and 3.5–4.0°C (B2). According to the climate projections, the expected increase of mean temperature in summer is between the expected warming of the maximum temperature and that of the minimum temperature. In case of spring, the expected temperature increase inside Hungary is 2.8–3.3°C (for A2 scenario) and 2.3–2.7°C (for B2 scenario).

Fig. 2 summarizes the expected mean seasonal warming for Hungary in case of A2 and B2 scenarios. In general, the expected warming by 2071–2100 is more than 2.4 °C and less than 5.1 °C for all seasons and for both scenarios. Expected temperature changes for the A2 scenario are larger than for the B2 scenarios. The smallest difference is expected in spring (0.6–0.7 °C), and the largest in winter (1.0–1.1 °C). The largest daily mean temperature increase is expected in summer, 4.8 °C (A2) and 4.0 °C (B2). The smallest daily mean temperature increase is expected in spring (3.1 °C and 2.5 °C in case of A2 and B2 scenarios, respectively). Expected increase of the daily maximum temperature exceeds that of the daily minimum temperature by about 0.1–0.6 °C (the largest is in summer), except in winter when the seasonal average daily minimum temperature is projected to increase by 4.1 °C (using the A2 scenario) and 3.0 °C (using the B2 scenario), both of them are 0.1 °C larger than what is projected for the daily maximum temperature increase.

On the basis of seasonal standard deviation fields (*Bartholy et al.,* 2007), the largest uncertainty of the expected temperature change occurs in summer for both emission scenarios.

Similarly to mean temperature, expected seasonal increase of daily maximum and minimum temperatures in the Carpathian Basin was also mapped

(*Bartholy et al.,* 2007). *Fig. 3* compares the projected increases of the winter and summer average daily maximum temperatures for the A2 and B2 scenarios. It can be seen that the spatial structure of the expected warming is similar to that of the expected daily mean temperature increase (*Fig. 1*), but in case of the maximum temperature the projected warming is larger by about 0.1–0.2 °C in winter and 0.3–0.4 °C in summer than in case of the mean temperature.

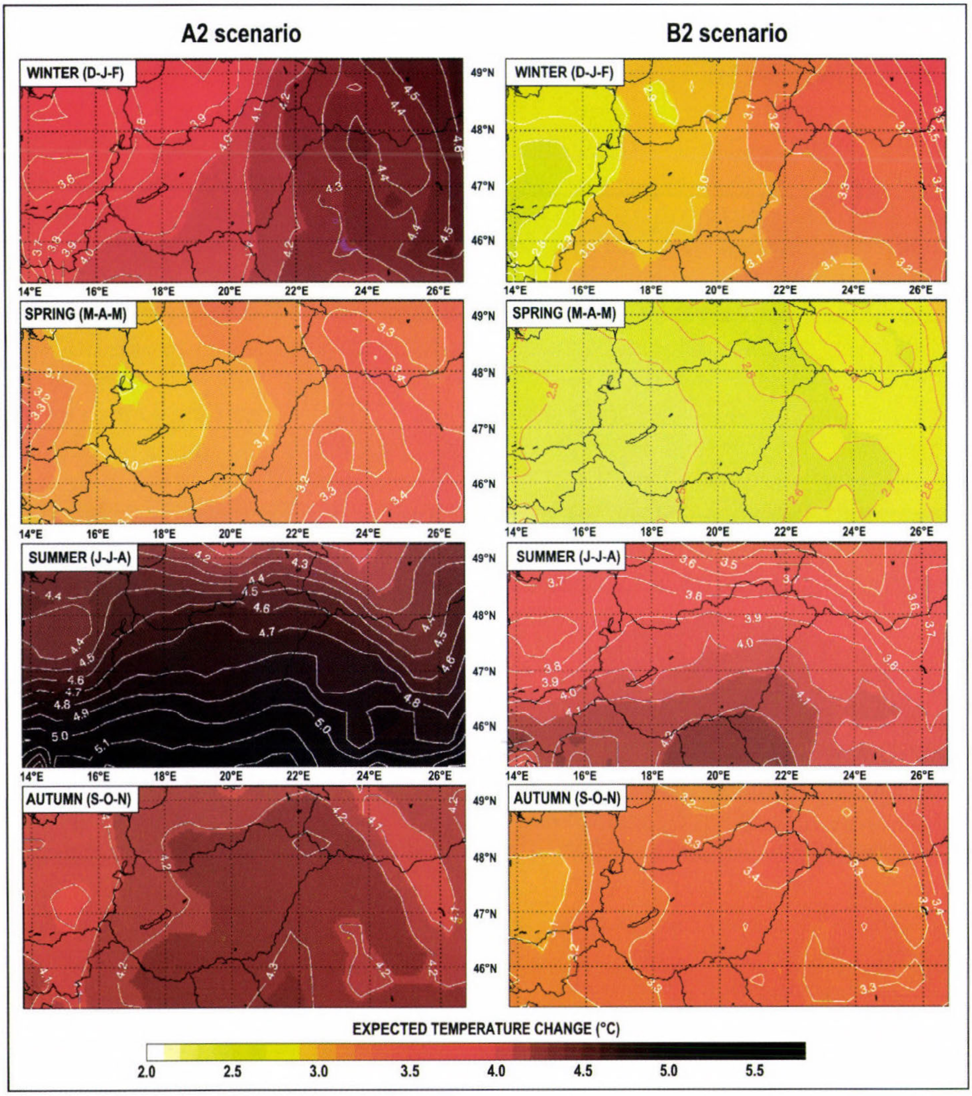

Fig. 1. Seasonal temperature change (°C) expected by 2071–2100 for the Carpathian Basin using the outputs of 16 and 8 RCM simulations in case of A2 and B2 scenarios, respectively (reference period: 1961–1990).

Table 2. Expected increase in mean, maximum, and minimum temperatures (°C) by 2071–2100 for Hungary in case of A2 and B2 scenarios using 16 and 8 RCM simulations, respectively (reference period: 1961–1990)

Temperature	Scenario	Winter (DJF)	Spring (MAM)	Summer (JJA)	Autumn (SON)
Mean	A2	3.7–4.3	2.9–3.2	4.5–5.1	4.1–4.3
	B2	2.9–3.2	2.4–2.7	3.7–4.2	3.2–3.4
Maximum	A2	3.7–4.2	2.8–3.3	4.9–5.3	4.3–4.6
	B2	2.6–3.0	2.4–2.6	4.0–4.4	3.3–3.5
Minimum	A2	3.8–4.6	3.0–3.2	4.2–4.8	4.0–4.2
	B2	2.8–3.5	2.3–2.7	3.5–4.0	3.0–3.2

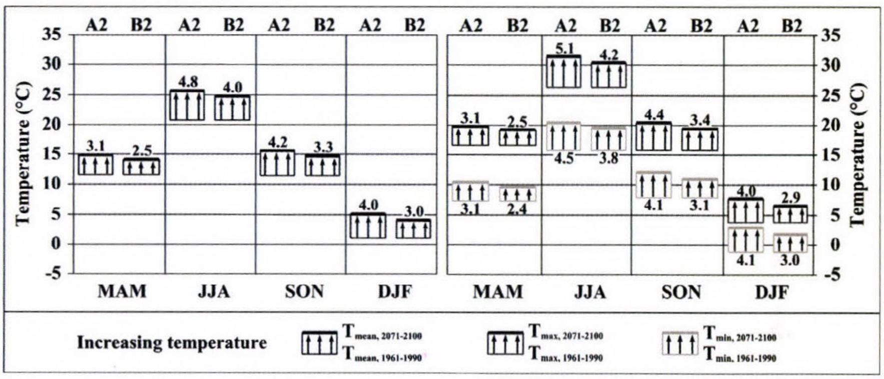

Fig. 2. Expected seasonal increase of daily mean, minimum, and maximum temperatures (°C) for Hungary (temperature values of the reference period 1961–1990 represent the seasonal mean temperature in Budapest).

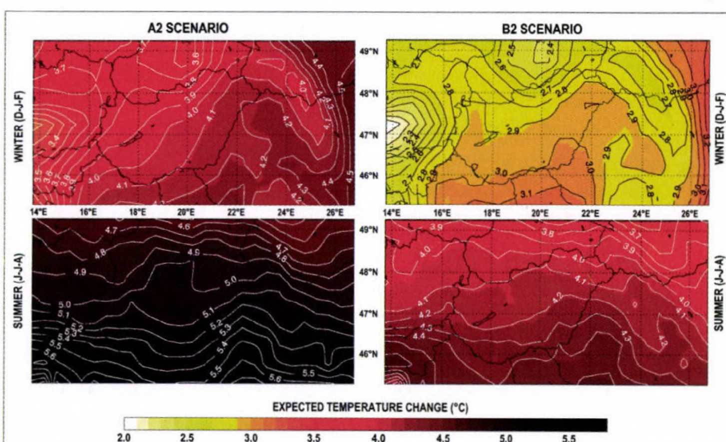

Fig. 3. Expected change of daily maximum temperature (°C) in winter and summer by 2071–2100 for the Carpathian Basin using the outputs of 16 and 8 RCM simulations in case of A2 and B2 scenarios, respectively (reference period: 1961–1990).

The expected trends of the extreme temperature indices are compared in *Fig. 4* for A2 and B2 scenarios using the daily temperature outputs of the regional climate modeling experiments (both for the 1961–1990 and 2071–2100 periods) of four different institutes (i.e., DMI, ICTP, KNMI, and ETHZ). The annual values of the indices are calculated as a spatial average of all the grid points located in Hungary, and then, the expected change is determined. According to the results, negative extremes are expected to decrease, while positive extremes tend to increase significantly. Both imply regional warming in the Carpathian Basin. The largest increase due to this warming trend can be expected in case of extremely hot days (Tx35GE), hot nights (Tn20GT), hot days (Tx30GE), warm nights (Tn90), and warm days (Tx90) by more than 100%. The expected changes are larger in case of the more pessimistic A2 emission scenario than in case of B2, the ratio is about 1–3. The expected warming trends of all the temperature indices are completely consistent with the detected trend in the 1961–2001 period (*Bartholy* and *Pongrácz*, 2006, 2007).

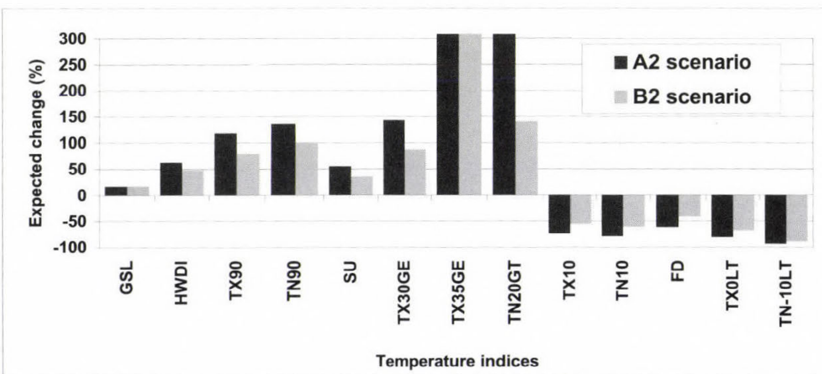

Fig. 4. Expected change of the extreme temperature indices in case of A2 and B2 scenarios (2071–2100) based on the daily outputs of the regional climate models of DMI, ICTP, KNMI, and ETHZ (reference period: 1961–1990).

In order to evaluate the model performance, temperature bias is determined for each RCM output fields using the simulations for the reference period (1961–1990), and the CRU (Climate Research Unit of the University of East Anglia) database (*New et al.*, 1999). In general, the RCM simulations overestimate the temperature in most parts of the Carpathian Basin, however, small underestimation can be seen in the western and northeastern boundary of the selected domain (*Bartholy et al.*, 2007). The largest overestimation can be detected in the southern part of Hungary (1.0–1.5 °C). In the northern part of Transdanubia and the northern part of the Great Plains the temperature is overestimated by 0.5–1.0 °C, while in the northeastern part of the country the overestimation is only 0–0.5 °C.

3.2. Precipitation

Similarly to temperature projections, composites of mean seasonal precipitation change and standard deviations are mapped for both A2 and B2 scenarios for the 2071–2100 period. *Fig. 5* presents the expected seasonal precipitation change for A2 and B2 scenarios (left and right panel, respectively) for the Carpathian Basin. The annual precipitation sum is not expected to change significantly in this region (Bartholy et al., 2003), but it is not valid for seasonal precipitation. According to the results shown in Fig. 5, summer precipitation is very likely to decrease (also, slight decrease of autumn precipitation is expected), while winter precipitation is likely to increase considerably (slight increase in spring is also expected).

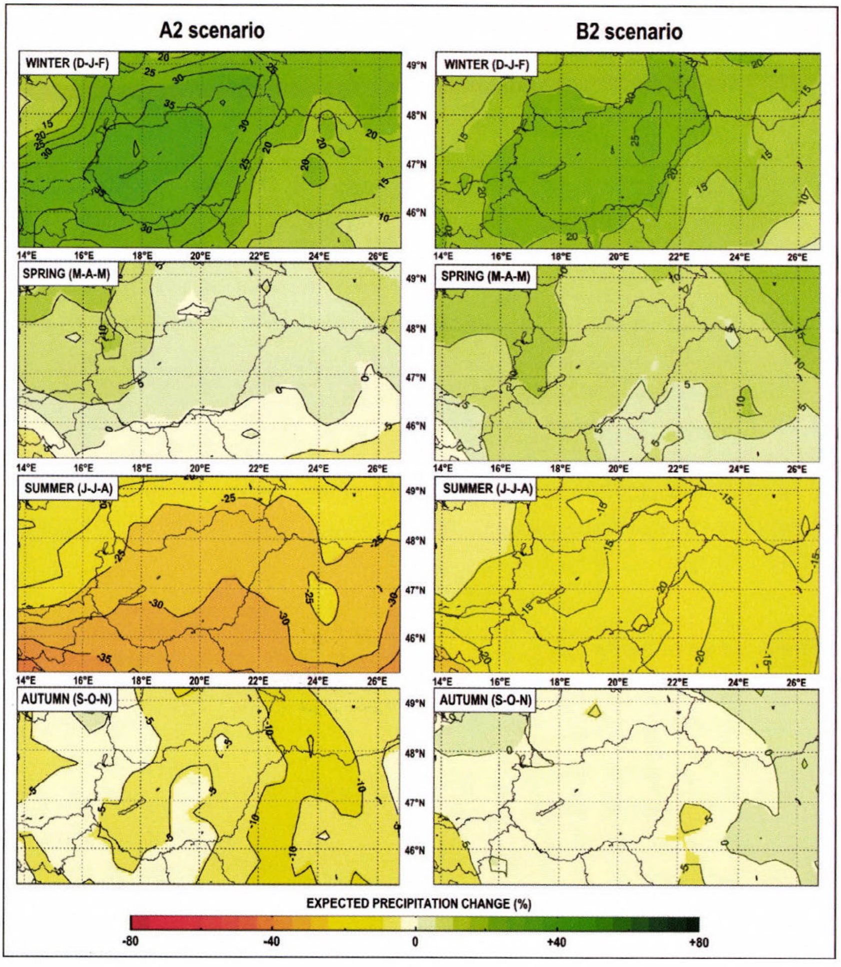

Fig. 5. Seasonal precipitation change (%) expected by 2071–2100 for the Carpathian Basin using the outputs of 16 and 8 RCM simulations in case of A2 and B2 scenarios, respectively (reference period: 1961–1990).

Table 3 summarizes the intervals of seasonal precipitation change for Hungary. In summer, the projected precipitation decrease is 24–33% (A2) and 10–20% (B2). In winter, the expected precipitation increase is 23–37% (A2) and 20–27% (B2). Based on the seasonal standard deviation values (*Bartholy et al.*, 2007), the largest uncertainty of precipitation change is expected in summer, especially, in case of A2 scenario (the standard deviation of the RCM results exceeds 20%).

Table 3. Expected mean precipitation change (%) by 2071–2100 for Hungary in case of A2 and B2 scenarios using 16 and 8 RCM simulations (reference period: 1961–1990)

Scenario	Winter (DJF)	Spring (MAM)	Summer (JJA)	Autumn (SON)
A2	(+23) – (+37)	0 – (+10)	(–24) – (–33)	(–3) – (–10)
B2	(+20) – (+27)	(+3) – (+12)	(–10) – (–20)	(–5) – 0

The expected seasonal change of precipitation for Hungary in case of A2 and B2 scenarios are summarized in *Fig. 6*. Black and grey arrows indicate increase and decrease of precipitation, respectively. According to the reference period 1961–1990, the wettest season was summer, then less precipitation was observed in spring, even less in autumn, and the driest season was winter. If the projections are realized, then the annual distribution of precipitation will be totally restructured, namely, the wettest seasons will be winter and spring (in this order) in cases of both A2 and B2 scenarios. The driest season will be summer in case of A2 scenario, while autumn in case of B2 scenario. On the base of the projections, the annual difference between the seasonal precipitation amounts is expected to decrease significantly (by half) in case of B2 scenario (which implies more similar seasonal amounts), while it is not expected to change in case of A2 scenario (nevertheless, the wettest and driest seasons are completely changed).

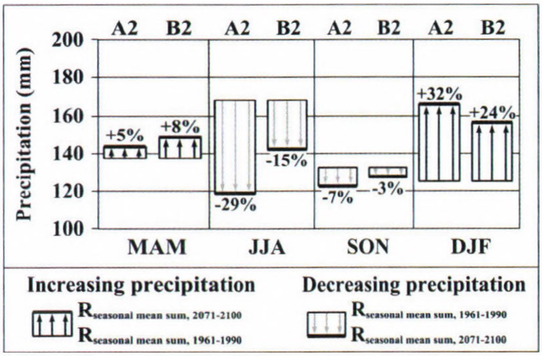

Fig. 6. Expected seasonal change of mean precipitation (mm) for Hungary (increasing or decreasing precipitation is also indicated in %). Precipitation values of the reference period 1961–1990 represent the seasonal mean precipitation amount in Budapest.

Table 4. Expected change of extreme precipitation indices in case of A2 and B2 scenarios (%) (2071–2100) based on the daily outputs of the RCMs of DMI, ICTP, KNMI, and ETHZ (reference period: 1961–1990). In case of the detected trends, signs in parentheses indicate regional mean coefficients being not significant at 95% level.

Precipitation index	**A2 scenario**			**B2 scenario**			**Detected trend**
	Year	**January**	**July**	**Year**	**January**	**July**	**1976–2001**
Rx1 (R_{max})	+17	+29	–2	+13	+23	–5	–
Rx5 ($R_{max,5\ days}$)	+10	+26	–11	+11	+17	–11	+
SDII (R_{year}/RR1)	+10	+16	+13	+7	+12	+1	(+)
R95 ($R_{day} \geq R_{95\%,1961\text{-}90}$)	+7	+60	–30	+14	+35	–22	+
R75 ($R_{day} \geq R_{75\%,1961\text{-}90}$)	–9	+19	–35	+0	+8	–21	+
RR20 ($R_{day} \geq$ 20 mm)	+60	+233	+66	+68	+212	–24	+
RR10 ($R_{day} \geq$ 10 mm)	+14	+95	–11	+20	+58	–14	+
RR5 ($R_{day} \geq$ 5 mm)	–1	+52	–30	+7	+28	–22	(–)
RR1 ($R_{day} \geq$ 1 mm)	–10	+19	–31	–2	+6	–19	–
RR0.1 ($R_{day} \geq$ 0.1 mm)	–11	+9	–3	–3	+1	–10	–
R95T ($\Sigma R_{day:\ when\ R_{day}>R_{95\%,1961\text{–}90}}/R_{total}$)	+16	+27	+9	+14	+23	+0	+

Table 4 summarizes the expected future trends of the extreme precipitation indices determined using the climate simulations of four selected RCMs (i.e., HIRHAM4 of the DMI, RegCM of the ICTP, RACMO2 of the KNMI, and CHRM of the ETHZ) for the 1961–1990 and 2071–2100 periods. Expected changes of annual precipitation indices are generally consistent with the detected trends in the last quarter of the 20th century (*Bartholy* and *Pongrácz*, 2005, 2007). However, the expected regional increase or decrease is usually small (not exceeding 20% in absolute value), except of RR20, the number of very heavy precipitation days. Much larger positive and negative changes are projected in January and July, respectively, on the base of the RCM simulations in case of the A2 and B2 scenarios. These results together with the composite maps shown in Fig. 5 suggest that the climate tends to be wetter in January and drier in July in the Carpathian Basin. Since the projected increases of the RR20, RR10, and R95 (these indices describe very extreme precipitation events) exceed 60% in January in case of A2 scenario, and the expected increases of RR0.1 or RR1 (these indices are not related to extreme precipitation) is 9% and 19%, respectively, the extreme precipitation events are expected to become more

intense and more frequent in January. Similar but smaller changes are expected in case of B2 scenario. Furthermore, drought is projected to become more severe in July by the end of the 21st century, which can be derived from the robust decrease of precipitation indices. The largest decrease rates (exceeding 30%) in July are expected in case of the R75, RR1, RR0.1, RR5, and R95 indices for the A2 scenario. The projected monthly changes are smaller for the B2 scenario.

The expected changes of R95 (number of very wet days) are illustrated in *Fig. 7* using annual and monthly (January and July) changes of grid point values of the extreme climate indices for A2 (upper maps) and B2 (lower maps) scenarios. Blue circles in the maps indicate expected increase, while yellow and red circles imply expected decrease. The size of the circles corresponds to the magnitude of the expected changes. In case of the annual change, the expected increasing rate between 2071–2100 and 1961–1990 in Hungary is about 9% and 18% on average using the A2 and B2 emission scenarios, respectively. Much larger changes are projected in January, namely, +59% and +41% for the country. Opposite changes can be expected in July, the average decrease is expected about 28% (A2) and 23% (B2) for the grid points located in Hungary.

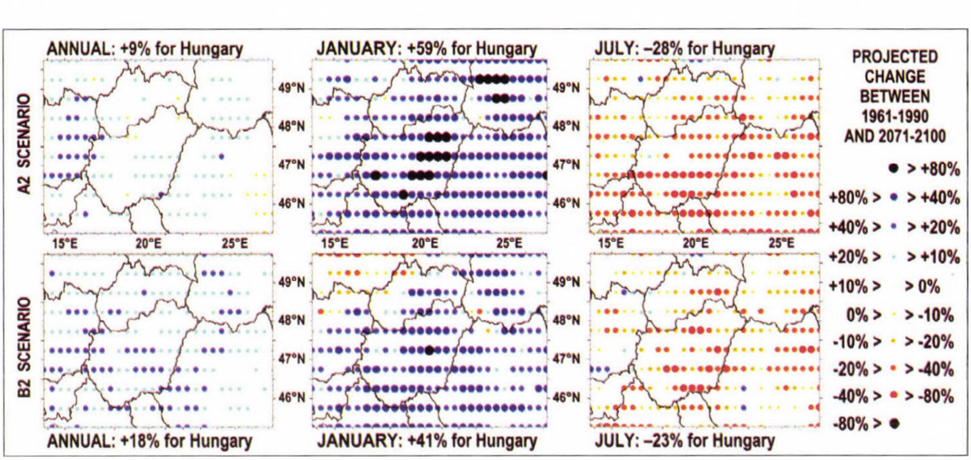

Fig. 7. Expected change of annual and monthly number of very wet days (R95) in case of A2 and B2 scenarios (2071–2100) compared to the reference period (1961–1990). Maps are determined using simulated daily precipitation amounts of the regional climate model of DMI.

In order to evaluate the model performance, precipitation bias is determined for all the RCM output fields using the simulations for the reference period (1961–1990), and the CRU database (*New et al.*, 1999). In general, the RCM simulations overestimate the precipitation in most parts of the Carpathian Basin, however, underestimation can be seen in the southwestern part of the region (*Bartholy et al.*, 2007). In Hungary, the bias is not exceeding 15% in absolute values. The precipitation is slightly underestimated in the western/-

southwestern part of the country, while precipitation in the other large parts (including the entire Great Plains and the eastern part of Transdanubia) is slightly overestimated.

4. Conclusions and discussion

On the basis of the results shown in this paper, the following conclusions can be drawn using the RCM experiment outputs of the PRUDENCE project.

(1) Expected seasonal temperature increase for the Carpathian Basin in case of the A2 scenario is larger than in case of the B2 scenario, which is in good agreement with the expected global and European climate change results (*IPCC*, 2007). The smallest difference between the A2 and B2 scenarios is projected for spring (0.6–0.7 °C), while the largest for winter (1.0–1.1 °C).

(2) The largest daily mean temperature increase is projected for summer, 4.8 °C (A2) and 4.0 °C (B2), while the smallest seasonal warming is expected in spring, 3.1 °C (A2) and 2.5 °C (B2).

(3) The largest increase of maximum and minimum temperatures is expected also in summer for both scenarios. In case of maximum temperature, the intervals of the expected warming are 4.9–5.3 °C (A2) and 4.0–4.4 °C (B2), while in case of minimum temperature, these intervals are 4.2–4.8 °C (A2) and 3.5–4.0 °C (B2). Expected increase of the daily maximum temperature exceeds that of the daily minimum temperature, except in winter.

(4) The extreme temperature indices associated with cold climatic conditions are projected to decrease in the Carpathian Basin by 2071–2100 while the positive extremes tend to increase significantly. The expected changes of the extreme temperature indices are larger in case of the A2 scenario than in case of the B2 scenario.

(5) The annual precipitation sum is not expected to change significantly in this region, but it is not valid for seasonal precipitation sums. Summer precipitation is very likely to decrease, furthermore, slight decrease of autumn precipitation is expected. On the other hand, winter precipitation is likely to increase considerably, and slight increase in spring is also expected.

(6) The projected summer precipitation decrease is 24–33% (A2) and 10–20% (B2), while the expected winter precipitation increase is 23–37% (A2) and 20–27% (B2).

(7) In the reference period (1961–1990), the wettest season was summer, while the driest season was winter. If the projections are realized, then the annual distribution of precipitation will be totally restructured. Namely, the wettest season will be winter in case of both A2 and B2 scenarios. The driest season will be summer in case of A2 scenario, while autumn in case of B2 scenario.

(8) Expected changes (for 2071–2100) of annual precipitation indices are small, but generally consistent with the detected trends in 1976–2001. The projected changes in winter and summer are opposite to each other, which means that large positive and negative changes of monthly precipitation indices are projected in January and July, respectively. Projected increase of very extreme precipitation events exceeds 60% in January, while the expected increases of not extreme precipitation indices do not reach 20%. These results imply that the extreme precipitation events are expected to become more intense and more frequent in January. Furthermore, drought is projected to become more severe and a general decrease of extreme precipitation indices is expected in July.

The analysis discussed in this paper is based on the PRUDENCE simulations, which means that only very few GCMs (mainly HadAM3H/HadCM3, some RCM experiments used ECHAM4/OPYC, and ARPEGE/OPA) are used as driving data of RCMs, which can be considered as limitations of the presented analysis. In an earlier paper (*Bartholy et al.,* 2003), 16 GCM outputs (i.e., ECHAM1, ECHAM3, ECHAM4, HadCM2, UKHI-EQ, UKTR, GFDL-TR, NCAR-DOE, UIUC-EQ, CGCM1-TR, CCC-EQ, BMRC-EQ, CSIRO1-EQ, CSIRO2-EQ, CSIRO-TR, and CCSR-NIES) are analyzed for Hungary in case of A1, A2, B1, and B2 scenarios. The results of the multi-GCM analysis are very similar to most of the findings of the present paper. The quartile range of the expected seasonal temperature change by the end of the 21st century is 3.0–5.5°C in winter, 2.1–3.9°C in spring, 3.0–4.6°C in summer, and 3.0–4.5°C in autumn in case of A2 scenario. The expected temperature increase is smaller for B2 than for A2 scenario. The quartile intervals for the B2 scenario are as follows: 2.0–3.8°C in winter, 1.5–2.5°C in spring, 2.0–3.1°C in summer, and 2.0–3.0°C in autumn. Thus, the projected warming is somewhat smaller than the expected temperature increase of the RCM simulations of PRUDENCE in most of the seasons except winter. However, one must not forget that the horizontal resolution is far more coarse in case of the GCMs (where only 1 or 2 gridpoints represent the entire area of Hungary) than RCMs. For the seasonal precipitation projections the GCM quartile ranges are also considerably smaller, especially, in case of winter and summer (the sign of the projected changes are the same as in the RCM simulations). The GCMs suggest that wetter winters and drier summers are expected by the end of the 21st century (the quartile intervals are (+5%)-(+25%) for A2 and (+2%)-(+15%) for B2 in winter, and (–2%)–(–24%) for A2 and (–2%)–(–15%) for B2 in summer). The projected precipitation changes in spring and autumn are very small (around zero), which also supports the RCM-based results discussed in the present paper.

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Regional change of climate extremes over Hungary based on different regional climate models of the PRUDENCE project

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Abstract—On the basis of different regional climate model (RCM) outputs of the PRUDENCE project, several precipitation-, temperature-, and wind-related extreme parameters were investigated at the Hungarian Meteorological Service: the occurrence of extreme precipitation events, the rate of frost, summer, hot, and extremely hot days, the number of heat waves, hot and freezing periods, and the frequency of the maximum wind speed exceeding given thresholds. The changes of these extreme events were computed for the period of 2071–2100 with respect to the reference period of 1961–1990 focusing on the Hungarian territory. The chosen regional models, which were driven with the same or similar general circulation models, are using 50 km horizontal resolution and two (A2 and B2) climate change scenarios. The investigations based on several models serve as an excellent opportunity to explore those uncertainties in the projections, which are due to the different regional climate models and different emission scenarios. Besides the abovementioned analysis of the future trends, the results of the reference period were validated with Hungarian (gridded) observational time series. In the paper the evaluation of the regional extreme parameters for the past over the Carpathian Basin is briefly introduced, and the changes of these extreme characteristics are summarized based on the RCM outputs of the PRUDENCE project. The results indicate, that by the end of the 21st century the number of days with precipitation would slightly decrease over Hungary, whereas the frequency of the days with heavy precipitation would expectedly be enhanced. The warm extremes, heat waves, and hot periods will occur more often, which were accompanied by the reducing number of cold extreme events. The occurrence of intensive and stormy winds will likely increase, however, the projected change has very small magnitude.

Key-words: regional climate modeling, PRUDENCE project, extreme indices, uncertainty, regional climate change

1. Introduction

The spatially coarse (recently around 100 km) resolution global models are unable to correctly simulate extreme climate characteristics since their low "coverage" smoothes out the extreme values otherwise present in the atmosphere. Since the raw results of global climate models do not provide sufficient details, regionalization techniques are needed to obtain more information about the regional aspects of the climate change. Additionally to the application of higher or variable resolution general circulation models, two further methods are known for gaining smaller scale information based on the global results: the statistical downscaling (*Wilby et al.,* 1998) and the technique with the use of high-resolution limited area regional climate models (*Giorgi* and *Bates*, 1989). Hereafter the present article is uniquely dealing with results obtained with this dynamical downscaling technique based on regional climate models.

The regional climate models belong to the dynamically-based techniques, which physically refine the raw global results on regional scale. In that case the regional model is focusing only on a selected limited area (e.g., on Europe) with finer horizontal resolution, and the large scale processes are taken into account by the (lower – like sea surface temperature – and lateral boundary) forcings provided by the global results. Due to the higher resolution not only a more precise description of the surface characteristics (e.g., the orography) is possible, but also the dynamical processes accounted by this kind of models are certainly adapting to these more accurate conditions.

In spite of all the advantages coming from the fine resolution, today's regional climate models and their simulations are still exacerbated by multiple deficiencies (which can vary from one model to other one), which are intensively studied by a number of international cooperations initiated in last decade (see e.g., *Jacob et al.,* 2007). Nevertheless, for satisfying the increasing demands the models are also applied to realize climate change simulations parallelly with the model developments. For that reason it is crucial at the design of the experiments for the future to consider not only single, but also several simulations of various models, because only the ensemble approach provides appropriate tool to specify the uncertain (and certain) aspects in the projections.

Inevitably the most important regional climate modeling project, which already gives concrete climate projections for Europe with relatively high resolution, is the PRUDENCE project (Predicting of Regional Scenarios and Uncertainties for Defining European Climate Change Risks and Effects, *Christensen et al.,* 2007). The main scientific objectives of the project were, on the one hand, to provide high-resolution regional climate change projections for the period of 2071–2100 and, on the other hand, to characterize the reliability of the climate change projections, with special emphasis on the distinction of the obtained variabilities coming from the differences between the regional models and the internal variability of the climate system. The results of the project serve as good basis to the ensemble consideration of climate change, since numerous model simulations were carried out with a range of global and regional climate models. The uncertainties in the projections did not purely come from the differences between the applied climate models (from the dissimilarities of their dynamical core and physical parameterizations), but also the future tendencies were forced by two basically different scenarios (one from the pessimistic and one from the optimistic groups) for greenhouse gas and aerosol emissions. The outcomes and outputs of the regional simulations of the PRUDENCE project have been public since the end of the project, and they have been directly accessible from the project's web page (http://prudence.dmi.dk) since 2006.

Being one of the essential indicators of the climate change, the extreme events and their future tendencies are intensively studied area of the climate researches. In 1997, the workshop on "Indices and Indicators for Climate Extremes" (*Karl et al.*, 1999) and later on the CCl/CLIVAR (World Meteorological Organization – Commission for Climatology/Climate Variability and Predictability) working group of World Meteorological Organization are dedicated to define extreme indices for the different meteorological parameters (mainly for the temperature and precipitation) in order to establish their common use. The STARDEX project (Statistical and Regional dynamical Downscaling of Extremes for European regions; *Goodess,* 2003) was initiated in 2001 to comprehensively evaluate the statistical and dynamical downscaling methods in order to reconstruct the observed past extremes and to construct regional scenarios for the future. In the framework of STARDEX, the past tendencies of several chosen extreme indices were analyzed in detail for Europe based on long observational time-series (e.g., *Haylock* and *Goodess*, 2004), and furthermore, the model simulations of the PRUDENCE project provided a good basis for the intercomparisons with the statistical methods (e.g., *Schmidli et al.,* 2007). The PRUDENCE's model simulations were thoroughly validated (for the mean precipitation, minimum, maximum, and mean temperature) by *Jacob et al.* (2007) for eight geographical regions in Europe. The projections were exhaustively investigated in the context of extremes by *Beniston et al.* (2007), which gave a detailed overview about the change of heat waves, heavy precipitation, drought, wind storms, and storm surges based on several RCMs' simulations; *Schär et al.* (2004) found that the future temperature variability will intensify with the largest degree in Central and Eastern Europe bringing severe consequences to the (increasing) number of heat waves; despite the general summer precipitation reduction and the warming trends projected by the majority of the RCMs over relevant part of the continent; *Christensen* and *Christensen* (2003) showed that there are many regions where enhancing frequency of the large precipitation events can be expected for the future together with more frequent flooding episodes. Particularly for the Carpathian Basin several studies aimed to explore and detect the trends of extreme events in last decades mainly on the basis of observational datasets: the work presented in

Bartholy and *Pongrácz* (2007) was carried out on long time series of Hungarian station data, while by *Lakatos et al.* (2007) already the homogenized time series were analyzed.

Present article is intended to provide an overview about the outcomes of the efforts, which have been made at the Hungarian Meteorological Service in order to estimate the future trends of the extreme events over Hungary based on the results of the regional climate models applied in the PRUDENCE project. The article is structured as follows: in the next section, on the one hand, a limited overview is provided about various sources of the uncertainties in the regional projections of the PRUDENCE project and, on the other hand, a brief description is given about the investigations carried out by the Hungarian Meteorological Service for the Carpathian Basin on the basis of the results of different RCMs. Section 3 considers in detail the projected change of the investigated extreme characteristics of precipitation, temperature, and wind speed; finally, Section 4 discusses the conclusions based on the extreme characteristics presented in the previous section.

2. Methodology of the investigations for Hungary

To achieve the aforementioned objectives in the PRUDENCE project, a hierarchical model system was applied with complex interactions between its components: the large scale circulation was described by coupled atmosphere-ocean models (AOGCMs) through long transient climate change simulations on 300 km horizontal resolution. These AOGCMs provided the atmospheric radiative forcings and the matching sea-surface boundary conditions for the time-slice experiments (covering the "discrete" periods of 1961–1990 and 2071–2100) to be carried out by stand-alone advanced high (150 km) resolution atmospheric general circulation models (AGCMs). Finally, these refined global results served as initial and lateral boundary conditions for the finest resolution regional simulations, which already focused on the European region with 50 km grid spacing. The preference of the relatively far future projection period was motivated by the assumption, that the future signal will be in this manner strong enough to draw robust conclusions on the expected climate change. As far as radiative constraints for the future are concerned, two different SRES emission scenarios (*Nakicenovic et al.,* 2000) were considered in the project: the A2 and B2 ones, which provide pessimistic and optimistic realizations of the emission levels in the 21st century (see *Fig. 1*).

The complex system sketched above takes into account multiple sources of uncertainties (*Christensen et al.,* 2007):

1. The large scale forcings for the higher resolution AGCMs were produced by different AOGCMs;
2. Several AGCMs were used to conduct the higher resolution global runs;

3. The radiative forcings in the future for the global models were described by two greenhouse gas and aerosol emission scenarios;
4. 8 RCMs were integrated to provide regional climate projections for the future.

Therefore, the different kind of uncertainties in the model simulations can be characterized through multiple ensembles of model integrations. Besides analyzing the future tendencies of the extreme precipitation, temperature, and wind events focusing for our region of interest (i.e., Hungary), the present article is dedicated to assess only and uniquely those uncertainties in the projections, which are due to the different regional climate models and different emission scenarios.

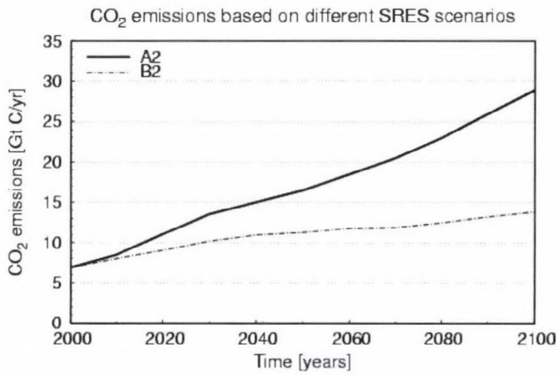

Fig. 1. The total future anthropogenic carbon dioxide emission (in gigatons of C per year) based on two reference scenarios: A2 (solid line) and B2 (chained line). (The diagram was constructed based on the data of *Nakicenovic et al.,* 2000.)

For that purpose daily outputs of five regional climate models applied in the PRUDENCE project were considered for Hungary: the HIRHAM, RegCM, PROMES, RCAO, and HadRM3P models (for additional information about the underlying model simulations see *Table 1*). The reasons for choosing these model simulations were, on the one hand, that for each integration the large scale forcings were provided by the same (or very similar in the case of HadAM3P, which is a successor of the HadAM3H model with few changes in the physical parameterizations) atmospheric general circulation model and, on the other hand, these RCMs were driven with both of the SRES scenarios (A2 and B2) applied in the project.

In the evaluation of the simulated extreme characteristics for the past, some observational time series were also taken into account in order to draw conclusions about the real spatial distribution of the examined parameters and to assess the performance of the models. For that purpose a gridded dataset on 0.1-degree horizontal resolution was applied, which was generated by interpolation based on Hungarian surface observations (*Szentimrey* and *Bihari*, 2007). This validation was limited to the daily precipitation amount and the daily minimum and maximum temperature.

Table 1. The main characteristics of the model simulations used for the investigations at the Carpathian Basin: the institute being responsible for the experiment, the applied regional model, the employed SRES scenario, and the global model which provided the driving data for the regional climate models

Institute	RCM	Reference	Scenario	Driving data
Danish Meteorological Institute (DMI)	HIRHAM	*Christensen et al.*, 1996	A2, B2	HadAM3H
Hadley Centre	HadRM3P	*Jones et al.*, 1995	A2, B2	HadAM3P
The Abdus Salam International Centre for Theoretical Physics (ICTP)	RegCM	*Giorgi* and *Mearns*, 1999	A2, B2	HadAM3H
Swedish Meteorological and Hydrological Institute (SMHI)	RCAO	*Döscher et al.*, 2002	A2, B2	HadAM3H
Universidad Complutense de Madrid (UCM)	PROMES	*Castro et al.*, 1993	A2, B2	HadAM3H

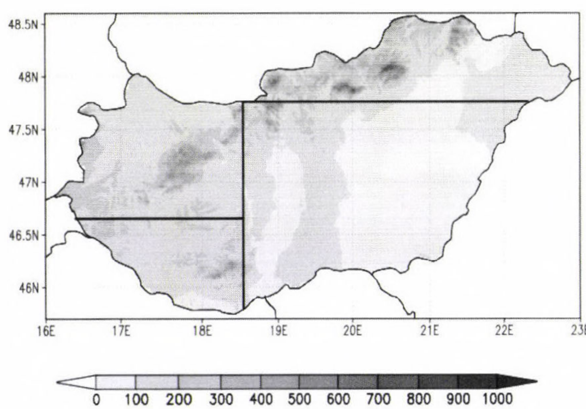

Fig. 2. Orography of the entire domain (i.e., Hungary) and sub-areas (separated with lines) defined for the investigations. (The orography on the map was generated from the data provided by the MISH software on 30-second horizontal resolution.)

In this study the threshold approach is used, i.e., it is examined whether certain fixed thresholds (whose majority was defined based on the recommendations of the WMO-CCl/CLIVAR Working Group) were exceeded or not for given parameters. The investigated changes of the different extreme parameters are always considered with respect to the reference (1961–1990) period of the same model (the changes with respect to the observations are not discussed). The analyses were carried out considering spatial averages not only over the entire country, but also for sub-areas within the country (namely, northeastern, northwestern, southeastern, and southwestern parts of Hungary).

These sub-domains were selected after simple consideration of the geographical and climatic conditions of Hungary (*Fig. 2*). The computations were carried out separately for each gridpoint over Hungary, and the values of figures and tables were obtained by averaging them for the entire country or the regions.

3. Results

Precipitation

Based on the results of the selected RCMs, the changes of the number of days with precipitation, heavy and very heavy precipitation (with daily amount exceeding 0.1, 10, and 20 mm, respectively) were investigated. Comparing the results for the reference period to the observed values it can be generally concluded, that the models mainly overestimate the number of events with small precipitation, while they rather underestimate the occurrence of the days with heavier precipitation; the only exception is the RegCM model, which projects too many events in every category (see *Fig. 3* and *Table 2*). As far as the future trends are concerned, it can be noticed, that for the A2 scenario the frequency of the days with precipitation will probably slightly decrease, however, at the same time some increase can be expected for the occurrences of the extreme precipitations (with the only exception of the Hadley Centre's model, which simulates rather decrease of the heavy precipitation with more than 10 mm daily amount). The former minor reduction proves to be much smaller for the B2 scenario, which is also valid for the days with very heavy precipitation (i.e., for the threshold of 20 mm/day), while in the case of events over the 10 mm daily amount the majority of the models projects slightly larger increase for the more optimistic B2 scenario. Nevertheless, it has to be remarked, that the tendencies concluded above mean very small changes, therefore, the differences between these signals are probably not significant. Therefore, for making sure of the correctness of these qualitative conclusions, the concrete values of the relative changes projected by the different models and the standard deviation between them are also calculated.

Table 3 provides some additional quantitative details to the conclusions mentioned above. Although for the thresholds of 0.1 and 10 mm the mean changes are similar to each other in magnitude (more or less around –10 and 10%, respectively, with some "extreme" values), the standard deviation for the higher threshold is too large compared to the magnitude of the mean change. This fact indicates that for the 10 mm/day threshold the signal is rather "uncertain", so this figure should be interpreted with special care. On the other hand, the situation is "better" for the 20 mm/day threshold (even though the absolute value of the standard deviation is higher than in the 10 mm/day case): the projected change is approximately 45% with a lower level (27%) of standard deviation, which can be interpreted in a way that the increase of heavy precipitation events is rather certain, however, its exact value is more uncertain (between around 5 and 65%).

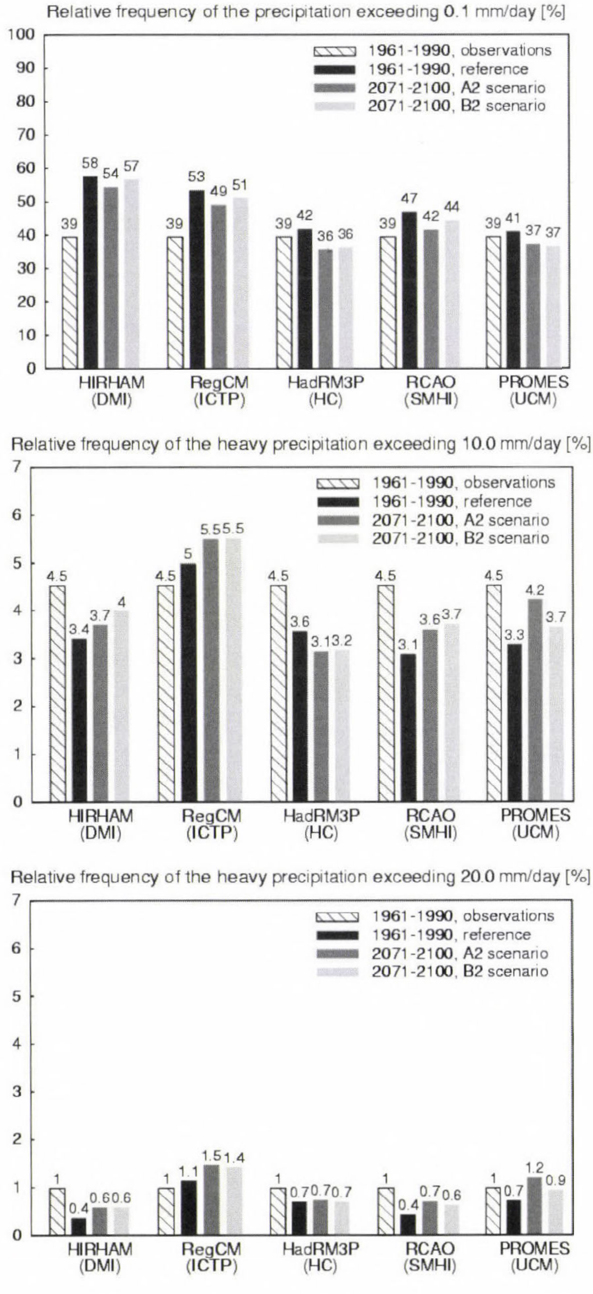

Fig. 3. Relative frequency of the daily precipitation amounts above different thresholds over Hungary. The groups of bars represent the different models, and the first two bars within each group denote the reference period (based on observations for the first one and on model results for the second one), the last two ones refer to the period of 2071–2100 with the use of different SRES scenarios (A2 and B2, respectively).

Table 2. The mean differences (in %) between the frequency of the simulated and observed extreme characteristics (R0.1, R10, R20: precipitation events exceeding 0.1, 10, and 20 mm/day, respectively; TN0: frost days; TX30: hot days) for the period of 1961–1990 over Hungary. The values of "Mean" represent average of these departures (in %)

Model	R0.1	R10	R20	TN0	TX30
HIRHAM	19	–1.1	–0.63	–6	4.1
RegCM	14	0.5	0.12	2	6.7
HadRM3P	3	–0.9	–0.28	1	10.7
RCAO	8	–1.4	–0.54	–14	5.6
PROMES	2	–1.2	–0.26	–5	–0.4
Mean	9	–0.8	–0.32	–4	5.3

Table 3. The changes (in %) of the frequency of different extreme characteristics (V5 and and V10: wind events exceeding 5 and 10 m/s in the maximum) for the period of 2071–2100 with respect to the period of 1961–1990 over Hungary based on different model simulations. The values of "Mean"/"Std. dev." represent average/standard deviation of the changes (in %) computed from the results of the different models. All the values are valid for the A2 SRES scenario

	Precipitation			Temperature				Wind speed	
Model	R0.1	R10	R20	TN0	TX30	Freezing period	Heat wave	V5	V10
HIRHAM	–5.5	8.5	64.3	–62.9	141.6	–54.2	58.2	–3.2	3.7
RegCM	–8.3	10.3	29.0	–67.3	87.6	–27.8	80.9	–	–
HadRM3P	–14.7	–11.9	4.7	–52.1	97.1	–44.4	46.2	4.8	17.9
RCAO	–11.6	16.6	62.4	–69.9	129.0	–62.7	59.1	1.5	31.1
PROMES	–9.5	28.6	65.6	–59.6	260.5	–46.4	196.4	0.2	14.2
Mean	–9.9	10.4	45.2	–62.4	143.2	–47.1	88.1	0.8	16.7
Std. dev.	3.5	14.7	27.3	7.0	69.3	13.0	61.8	3.3	11.3

Temperature

In the case of temperature, the changes of relative frequency for summer, hot, and extremely hot days (defined as days when the maximum temperature exceeds the 25, 30 and 35 °C, respectively) were investigated as "warm" extreme indices, while the tendency of frost days (defined as days when the minimum temperature is below 0 °C) was examined as "cold" extreme taking into account again both the observations and model results. For the warm parameters one can generally conclude, that for each of them frequency increase can be expected by the end of the 21st century, both for entire Hungary and for every sub-region. (Only the results related to hot days over Hungary are presented in *Fig. 4* and *Table 3.*) Although lots of differences can be noticed (e.g., already for the reference period) between the models, it can be generally pinpointed, that:

- The simulations for both scenarios indicate frequency increase of the warm extreme events;
- Between the two scenarios (A2 and B2), the B2 one shows more moderate changes (which is not surprising at all, because the B2 scenario is the more optimistic one, i.e., considering smaller anthropogenic emissions of greenhouse gases and aerosols, see *Fig. 1*);
- The *absolute* increase of the warm and hot days for the future exceeds in general with 10 percent according to the more pessimistic A2 scenario, while in the case of extremely hot days, the absolute increase is more moderate (around 4–8 percent).

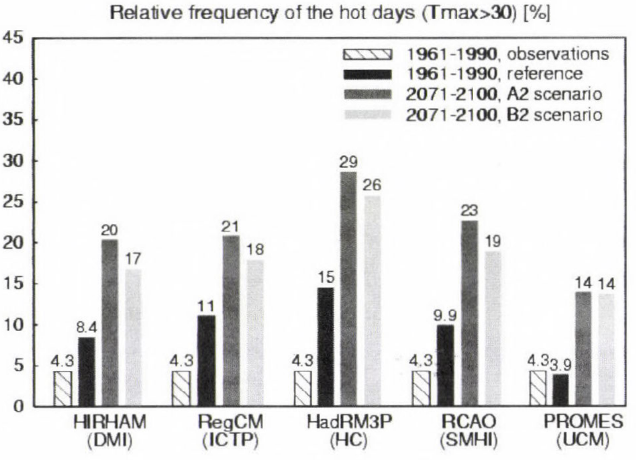

Fig. 4. Relative frequency of hot days over Hungary. The groups of bars represent the different models, and the first two bars within each group denote the reference period (based on observations for the first one and on model results for the second one), the last two ones refer to the period of 2071–2100 with the use of different SRES scenarios (A2 and B2, respectively).

More particularly, regarding the change of the number of hot days over Hungary it can be seen, that the majority of the investigated RCMs significantly overestimates the number of hot days for the past (*Fig. 4* and *Table 2*): the models simulate twice or even three times larger frequency than it was observed with the only exception of the PROMES model, which almost correctly reflects the true conditions (rather with a minor underestimation). In spite of the large uncertainty for the past, the projected positive tendency is obvious for every experiment (as it can be also easily read from *Table 3*). The mean of the signals over the entire country is 143% (i.e., the hot days will occur approximately 2.5 times more frequently in the future than in the past), and the simulated changes range the interval of 97–260%. The upper extreme (260%) is coming from the PROMES results and it is due to the fact that its reference is (correctly) the lowest among the models, and therefore, the relative increase is the largest (in spite of the fact that the PROMES model provides the lowest absolute change).

For the frost days, the RCMs behave rather differently from each other during the reference period: three of them underestimate the number of the cold extreme events, while the remaining two are rather perfect (with a very-very slight non-significant overestimation) – see *Fig. 5* and *Table 2*. The absolute errors do not have such large magnitude than it was the case for the hot days, due to the anyway more frequent occurrence of the event. The sign of the projected change is opposite with respect to the hot days: by the end of the 21st century, decrease of frost days has to be envisaged according to every experiment. On top of that, considering the very low value of the standard deviation (7%) in *Table 3* it can be stated with large confidence, that the simulated reduction of 60% can be identified as very sharp and convincing projection for the future. All this is valid not only for the A2 scenario, but also for the (more optimistic) B2 one with the restriction that the probable change is lower (about 40%; not shown).

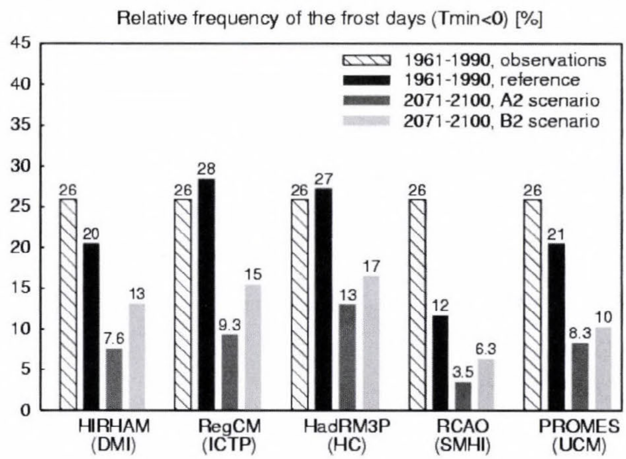

Fig. 5. Relative frequency of frost days over Hungary. The groups of bars represent the different models, and the first two bars within each group denote the reference period (based on observations for the first one and on model results for the second one), the last two ones refer to the period of 2071–2100 with the use of different SRES scenarios (A2 and B2, respectively).

In the case of temperature, not only the tendency of the occurrence of the days with maximum, minimum, and mean temperature exceeding given values, but also their persistence on consecutive days is of interest. For instance, from the aspects of human health the expected frequency of heat waves in future has also great importance, while for the building industry or forestry the changes of freezing periods in winter and hot periods in summer are also meaningful parameters to be considered. *Fig. 6* provides some information about the simulated frequency of heat waves (defined as periods of at least 3 consecutive days, when the daily mean temperatures exceed 25 °C) over Hungary both for the past (reference) and the future. The results of the five investigated models clearly indicate that the occurrence of this event will increase by the end of the 21st century with slightly different magnitudes for the individual model simulations, but with more than 50 percent in most of the cases for the A2 scenario (see *Table 3*). The mean of the signals projected by the ensemble of RCMs is approximately 88% due to the "outlier" value (196%) simulated again by the PROMES model (however, it has to be mentioned, that the future frequency of the heat waves produced by PROMES is in good agreement with the other models' result, and the reason for the large relative deviation is coming from the significant differences in the reference period.)

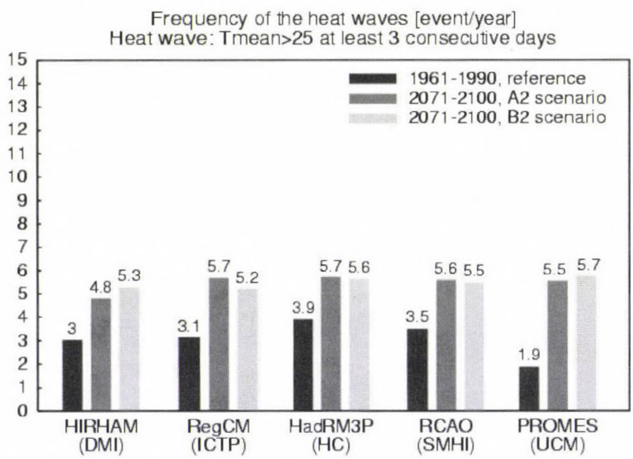

Fig. 6. Frequency of the heat waves over Hungary. The groups of bars represent the different models, and the first bar within each group denotes the reference period, the last two ones refer to the period of 2071–2100 with the use of different SRES scenarios (A2 and B2, respectively).

Regarding the hot periods (defined as periods of at least 3 consecutive days, when the daily maximum temperatures exceed 35 °C), a dramatic level of change is anticipated for the last decades of the 21st century: it will increase from the former 0.5–3 to 2–6 events per year (not shown). It is worth noting, that both in the case of heat waves and hot periods, there are no significant differences between the results for the two emission scenarios.

As far as the freezing periods (defined as periods of at least 3 consecutive days, when the daily minimum temperatures are not higher than 0 °C) are concerned, there is a large uncertainty between the models for the reference period (the results vary from 4 to 10 events annually – see *Fig. 7*), however, on the contrary, there is a good agreement between them regarding the future trends: the frequency of the freezing periods will uniformly decrease (with approximately 50% in the case of A2 scenario) – with large confidence as it is indicated by the especially low (13%) standard deviation value (*Table 3*). The sign of the change for the B2-case is the same, but its magnitude is smaller: about 30% (not shown).

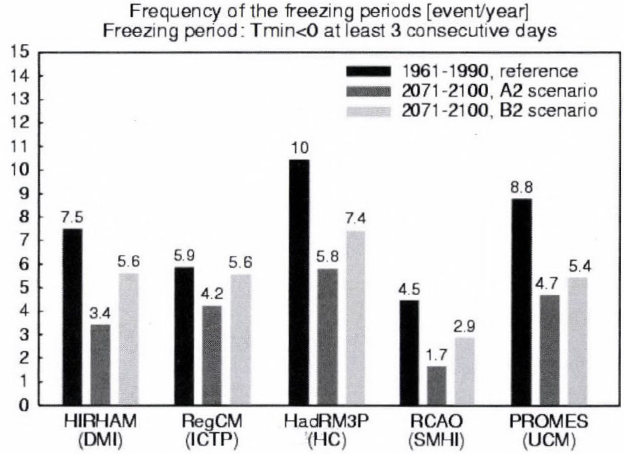

Fig. 7. Frequency of the freezing periods over Hungary. The groups of bars represent the different models, and the first bar within each group denotes the reference period, the last two ones refer to the period of 2071–2100 with the use of different SRES scenarios (A2 and B2, respectively).

It is worthwhile to pay special attention to the behavior of the PROMES model: its temperature simulation for the past seems to be the uniquely correct one compared to the observations in the case of warm values (remember the hot days), whereas in the cold range its performance is rather "ordinary" with some deficiency. Although in the case of persistence characteristics the observed values are not calculated and their occurrence is relatively rare over Hungary, it is rather clear, that less heat waves (and hot periods) are peculiar to the simulation of PROMES model for the past than it was projected by the other models, while the number of freezing periods is rather similar to the others. Another important feature is in that respect, that later (in the future) the model "compensates" its low level of the heat waves in the past: the simulated occurrence is almost the same as it is for the other models – it is not valid either for the hot (extremely hot and warm) days or the hot periods, however, the outstanding large magnitude of the changes leads to the conclusion, that the PROMES model projects much more heated climate conditions by the end of the 21st century than it was typical in the reference period.

Wind speed

The extreme characteristics' investigations for 10-meter wind speed take into account only the results of four regional climate models – the RegCM model is excluded due to the lack of wind data. Before the analyses of model results, maybe it is worthwhile to look at the spatial distribution of the relative frequency of mean wind speed exceeding given thresholds based on observational data (*Fig. 8*): the windiest parts of the country are in the elevated points of the North-Transdanubian regions (north from the Lake Balaton). Higher values occur also at the northwestern boundary of the country, and over the southeastern and northeastern part of the Great Hungarian Plain. (This spatial distribution can be explained by the topographical features of Hungary, namely that the typical northwesterly flow naturally enters the basin through the valley between the Alps and Carpathians, while the eastern part of the basin is under the influence of the mountainous flow blowing from the North Carpathian range.)

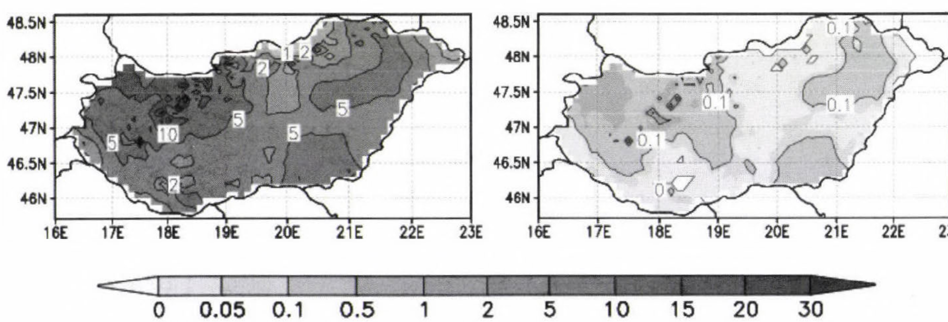

Fig. 8. Relative frequency (in %) of the observed daily mean 10-meter wind speed over Hungary exceeding different thresholds: 5 m/s on the left and 10 m/s on the right. The maps are generated on 0.1-degree horizontal resolution.

As far as the model simulations are concerned, firstly the tendencies for the entire country were examined for the relative frequency of such events, when the daily maximum of 10-meter wind speed exceeds given limit values. The range of investigated thresholds covers the interval between 0 and 20 m/s, however, in *Fig. 9* only the results of 5, 7, 10, and 14 m/s are presented, respectively. It is hard to conclude any significant tendency in the case of the lower daily wind maxima, while in the case of the higher ones, the trends are a bit more easily interpretable (as it is also clearly quantified in *Table 3* for the simulations driven by the A2 SRES scenario). Particularly, for the threshold of 5 m/s the relative changes projected by individual models are very small positive ones (except the HIRHAM model): the mean of the models' ensemble is 0.8%; while the standard deviation between the signals is too large (3.3%) compared to the mean change. On the contrary, the frequency of the daily wind maxima exceeding the threshold of 10 m/s indicates an increase with generally larger magnitude (16.7% in average) accompanied with a standard deviation (11.3%) remaining under the signal of the relative change. All this just means that the increase of the stronger wind events is rather significant with respect to the uncertain "situation" for the lower thresholds.

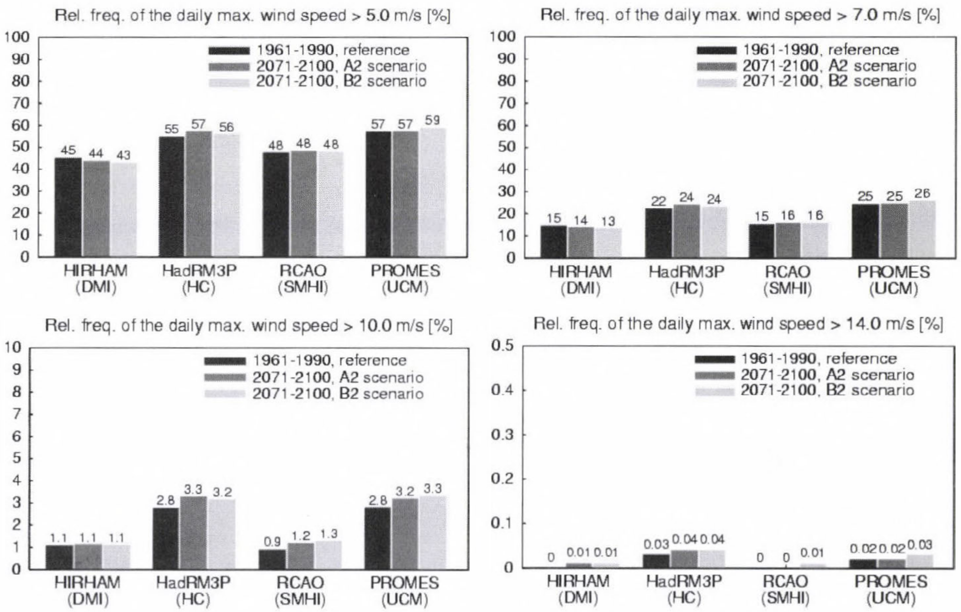

Fig. 9. Relative frequency of the simulated daily maximum 10-meter wind speed over Hungary exceeding different thresholds. The groups of bars represent the different models, and the first bar within each group denotes the reference period, the last two ones refer to the period of 2071–2100 with the use of different SRES scenarios (A2 and B2, respectively).

The separate examination of the results over different geographical regions provides further valuable insight into the future wind patterns. According to the quantitative results for the threshold of 10 m/s (*Table 4*), it can be generally pinpointed, that the more pronounced (and uniformly positive) changes are found over the least windy parts of the country, namely over the northeastern and southwestern regions, where also the standard deviations between the model results are the most "acceptable" (for the northwestern and southeastern parts of Hungary the standard deviations are too large with respect to the magnitude of the signal). This argumentation is not only valid for the ensemble mean, but also for the individual model results with the only exception for the RCAO model (which produces the strongest change besides the northeastern region also at the southeastern one). Furthermore, it is noteworthy, that the HIRHAM model simulates systematically the lowest degree of change for almost every sub-area (the only exception is the northeastern sub-domain).

Table 4. The changes (in %) of the frequency of the event, that the daily maximum of 10-meter wind speed exceeds 10 m/s, for the period of 2071–2100 with respect to the period of 1961–1990 over different regions (NW: Northwestern, NE: Northeastern, SE: Southeastern, SW: Southwestern Hungary, and HU: entire Hungary) based on different model simulations. The values of "Mean"/"Std. dev." represent average/standard deviation of the changes (in %) computed from the results of the different models. All the numbers indicate the simulation results driven by A2 SRES scenario, except the last column, where the values in the brackets refer to the B2 SRES scenario

Model	NW	NE	SE	SW	HU
HIRHAM	3.5	29.6	–1.2	10.5	3.7 (0.9)
HadRM3P	27.4	30.4	11.4	32.2	17.9 (13.3)
RCAO	24.1	35.9	37.9	27.2	31.1 (42.2)
PROMES	11.8	17.0	12.6	20.6	14.2 (18.5)
Mean	16.7	28.2	15.2	22.6	16.7 (18.7)
Std. dev.	11.1	8.0	16.4	9.4	11.3 (17.3)

The results for the lower threshold values slightly differ from all this, particularly for the 5 m/s (not shown): the average signals have quite similar magnitudes for each region, they do not reach (except for the northeastern part of Hungary) the –1 or 1 percent, while the standard deviation between the simulated changes exceeds the degree of the change in every case. The HIRHAM model is again in noticeable contrast with its counterparts: it is the only model, which projects a decrease of the frequency of the event for each sub-area. This behavior of HIRHAM (i.e., non-significant decrease of the frequency of lower wind maxima and almost negligible increase of the frequency of higher maxima) might indicate that its simulated circulation and mean wind patterns are a bit different from those of the other models.

It is also interesting to see, that in contradiction of the results concluded at the temperature extremes, there are two models (both for lower and higher thresholds of daily maximum), which project larger changes for the more optimistic B2 scenario.

According to all this, it can be generally said, that any tendentious change is rather concluded in the case of higher wind speeds, and according to the results, for the higher thresholds some compensation can be expected between the presently windiest and the less windy parts of Hungary; nevertheless, it should not be forgotten, that these signals are very-very small ones and their significance are doubtful and arguable.

4. *Summary, conclusions*

In the last years several efforts were carried out world-wide in order to estimate the regional impacts of the global climate change, from which the PRUDENCE project (completed in 2004) provided the first comprehensive projections for the European region. At the Hungarian Meteorological Service the 50 km resolution results of five regional climate models used in the project were analyzed, and the tendencies of precipitation-, temperature-, and wind-related extreme parameters were intensively examined providing a good basis for the preparation of National Climate Strategy of Hungary, which is a guideline for the Hungarian policy makers to define the main track of the adaptation policy to the impacts of the climate change in Hungary. The projected changes of the extreme characteristics were investigated for the period of 2071–2100 with respect to the period of 1961–1990 focusing on the territory of Hungary. The choice of these simulations was mainly motivated by the fact, that these RCMs were driven with both of the SRES scenarios (A2 being a pessimistic one and B2 being an optimistic one). With this type of consideration of model outputs only a part of the uncertainties in the projection can be specified, namely the uncertainties due to the application of different regional climate models and different emission scenarios. However, it has to be underlined, that in the PRUDENCE project much more model simulations were accomplished, which were carried out on the one hand with the use of other RCMs and on the other hand with the use of further driving global models. Therefore, the real spectrum of the uncertainties is surely broader, which fact was also confirmed by recent studies (e.g., in *Déqué et al.,* 2007 it was showed that the variability introduced by the choice of the driving GCM has the largest contribution to the range of uncertainty).

According to the results detailed above it can be generally concluded, that in spite of the fact, that between the individual model simulations there are lots of differences over Hungary, the main tendencies of the future extreme features are characterized rather similarly.

In the case of precipitation it is emphasized, that for the end of the 21st century the reduction of the number of days with precipitation has to be considered, while at the same time the frequency of the days with heavy (and very heavy) precipitation will expectedly increase (and consequently, the number of days with light precipitation will be reduced). These conclusions are valid for both of the applied SRES scenarios with generally more considerable level of the change for the more pessimistic one, however in the case of heavy precipitation over 10 mm daily amount, the B2 scenario provides larger increase. Nevertheless, it has to be mentioned here, that these changes have very small magnitude, therefore, the results have to be taken into account with careful consideration. It would be also useful to examine the seasonal distribution: e.g., in *Pongrácz et al.* (2008) it was concluded, that the precipitation events become more frequent in winter and more seldom in summer over the Carpathian Basin (based on the results of ETH's (Swiss Federal Institute of Technology) CHRM model, which model's results were not the subject of our study), but what is even more interesting, that the occurrence of extreme precipitation days will be intensified in winter and reduced in summer.

Regarding the temperature extremes, the model results render the increase not only for the individual warm extremes (warm, summer, and hot days), but also the heat waves and hot periods will occur more often. As further consequence of the regional climate change over Hungary, the frequency of frost days and freezing periods will be expectedly reduced. All this (i.e., the decrease of cold and increase of warm extremes) fits well to our view about the mean warming tendencies over Hungary. Additionally, it should be noticed, that compared to the other investigated parameters these temperature signals are quite sharp and convincing ones, it is especially valid for the cold temperature extremes. On the other hand, with regard the persistence characteristics further analyses would be desired, because on the basis of these results there is no information about the tendencies of the duration of heat waves, hot and freezing periods. For instance, since the three as well as the more than three consecutive days exceeding given threshold are considered with equal weight in the present analyses, the future situation with more and longer warm periods can be imagined with the same probability as the situation with more but shorter ones.

As far as the wind events are concerned, no significant changes could be detected in the range of lower and "ordinary" wind speed values, the occurrence of intensive and stormy winds will likely increase, however, the projected change has very small magnitude. An interesting issue is, that while for the temperature extremes the more pessimistic A2 scenario provides more dramatic signals uniformly for every model, in the case of wind, there are several models, where the optimistic B2 one simulates slightly more pronounced changes. Regarding the wind-related investigations it has to be mentioned, that the daily maximum wind speed is not the most appropriate indicator for the extreme storm events. In the background of this fact is, that in the case of the chosen RCMs, this variable was calculated purely based on the 10-meter wind speed without application of any gust parameterization, and this empirical formulation led to the under-representation of strong wind events in the simulations (further details are provided in *Rockel* and *Woth*, 2007).

It has to be mentioned, that the accomplished analyses were based on simple examinations, where it was checked, whether different fixed thresholds for given parameters were exceeded or not. Nevertheless, it is evidenced, that this fixed threshold approach is not satisfactory at every case, e.g., there are regions (gridpoints) and seasons, where and when the given thresholds are not considered as extremes, but "usual" values. For that reason it is planned to continue the analyses on the basis of the percentile approach with the further extensions for seasonal investigations and for several new extreme indices. Finally, as it was indicated by the results, in the case of certain extreme parameters not only the signals are modest, but also the absolute occurrence of the event. The question is naturally arising, whether these changes are statistically significant or not. The follow-on of the recent work aims to investigate the statistical significance of the obtained results in order to be in the position to have more solid conclusions regarding the future change of the extreme characteristics over Hungary.

The valuable outcomes of PRUDENCE project provide the first regional projections for Europe (for two emission scenarios); PRUDENCE was followed by the ENSEMBLES project, in which the main focus is on the pervasive quantification of the uncertainties originating from different sources in the regional climate simulations. Nevertheless, it is underlined, that these results do not substitute the further application of finer resolution climate simulations and analyses. These investigations are already ongoing in Hungary at the Hungarian Meteorological Service and Eötvös Loránd University with the use of adapted high-resolution regional climate models. Several simulations of four regional climate models (ALADIN-Climate, REMO, PRECIS, and RegCM) are already accomplished or planned to be carried out for the Carpathian Basin on high (25 and 10 km) resolution taking into account different emission scenarios (besides the widely used and rather realistic A1B also the A2 one) and lateral boundary conditions in order to compose a small ensemble, which will serve as a great opportunity to explore the certainties and uncertainties in the model results focusing over our area of interest.

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Regional photochemical model calculations for Europe concerning ozone levels in a changing climate

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Abstract—Regional photochemical model calculations were performed for three decadal time periods: 1991–2000, 2041–2050, and 2091–2100 under changing climate conditions for Europe. While the climatic conditions changed between the decades, all other input fields of the chemical model were held constant in order to separate climate effects from others. In particular, model results for summer ozone concentrations were investigated. These show increasing ozone values in response to higher temperatures and net radiation associated with increases in anthropogenic greenhouse gases. The increase of ozone is stronger in the second half of the 21st century than in the first half. In the course of the whole century, the average summer ozone maxima will rise by several ppbv over most parts of Europe with the highest change in the northwest of the continent. This increase suggests more frequent concentrations above legal thresholds in the future and is partly caused by higher emissions of biogenic hydrocarbons in the model calculation.

Key-words: photochemical transport model, tropospheric ozone, climate change, CECILIA project, ozone threshold level

1. Introduction

High ozone levels above legal thresholds affecting human health as well as vegetation are of primary interest in air quality research. Several factors affect

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ozone concentration, including the availability of ozone precursors, namely nitrogen oxides and volatile hydrocarbons, which are to a large fraction of anthropogenic origin. In addition, ozone formation is favored under certain meteorological conditions. Therefore, the question arises, what influence climate change will have in the future on the potential of ozone formation. Ozone concentration is in part controlled by the global background level formed by the long-range transport of pollutants and the exchange of air masses between the troposphere and stratosphere as the main mechanisms. However, over populated areas, anthropogenic emissions on local and regional scales often lead to high ozone concentration levels. Therefore, projections for future burdens of ozone should be made on a regional scale, at least.

Recently, there have been several studies with regional model calculations for Europe concerning air pollution under changing climate conditions. For example, *Meleux et al.* (2007) investigated summer ozone amounts over Europe with a 50 km resolution model by comparing two time slices of 30 years each, namely 1961–1990 and 2071–2100. *Forkel* and *Knoche* (2007) used a nested regional climate-chemistry model with a highest spatial resolution of 20 km over central Europe and compared the two time slices of 1991–2000 and 2030–2039. *Hedegaard et al.* (2008) had a resolution of 150 km in their model and inspected three decades (1990s, 2040s, and 2090s) for the Northern Hemisphere. In all of these studies, the anthropogenic emissions were kept unchanged for the future projections, so that their focus was on the effects of changing meteorological conditions. This approach is also applied in the present study.

This work was carried out within the European FP6 project CECILIA (Central and Eastern Europe Climate Change Impact and Vulnerability Assessment, http://www.cecilia-eu.org/). In this project, regional climate simulations with high spatial resolution are carried out for the target area. In addition, impact studies concerning hydrology, agriculture and forestry, as well as air quality are performed. For the latter, the model runs described in this study will be used to provide boundary concentrations for photochemical model calculations with 10 km resolution in smaller regional grids within the target area of this project. Three decadal time slices, namely 1991–2000, 2041–2050, and 2091–2100 were calculated.

It is not the purpose of this study to predict exact levels of air quality of the future until the year 2100, as there are too many unknown parameters such as the amount and composition of future anthropogenic emissions of air pollutants due to progress in technology as well as changes in land use. The latter is important, since it affects the distribution and amount of biogenic and anthropogenic emissions, and it is subject of man-made changes as well as of feedbacks from climate change. Similar to the studies by the other authors mentioned above, this study was performed to investigate the effect of climate change on ozone concentrations under the assumption that all parameters affecting air quality, except for the meteorological data, are kept unchanged.

2. *Description of the models and input data*

2.1. *RegCM and CAMx*

Meteorological input files for the photochemical model were taken from a transient climate run with the hydrostatic RegCM3 model (*Pal et al.*, 2007) performed at ICTP, that was driven at the lateral boundaries by the global ECHAM5 model under forcing from the SRES-A1B IPCC greenhouse gas scenario (*Nakicenovic et al.*, 2000) for the future projections. The spatial resolution of the model was 25 km × 25 km. A part of these calculations was performed for the EU-FP6 project ENSEMBLES (http://ensembles-eu.metoffice.com/).

The Comprehensive Air quality Model with eXtensions (CAMx), which is available at http://www.camx.com, from ENVIRON International Corporation (Novato, California) is an Eulerian photochemical dispersion model that allows for regional integrated "one-atmosphere" assessments of gaseous and particulate air pollution. Model version 4.40 was used (*ENVIRON*, 2006). The chemistry mechanism invoked was an extended Carbon Bond version 4 mechanism (*Gery et al.*, 1989). This mechanism includes 117 reactions – 11 of which are photolytic – and up to 67 species (37 state gases, up to 18 state particulates and 12 radicals).

The spatial resolution of the CAMx model grid was 50 km × 50 km and the domain had 94 × 102 grid cells. The domain's vertical profile contained 12 layers with varying thicknesses, extending up to 450 hPa. The 25 km RegCM results were upscaled to this resolution by averaging. The domains of the two models were the same. The grid covered most of Europe and parts of northern Africa as it may be seen in the figures, which display the whole domain. Time resolution of meteorological input was 6 hours, the emission input as well as the output of the photochemical model had a resolution of one hour.

The RegCM output was transformed to the format required by CAMx by a pre-processor program. Some of the fields could be taken directly like wind direction, wind speed, and temperature, while others had to be calculated analytically. The vertical diffusion coefficient needed by CAMx to model the vertical transport was calculated following the method by *O'Brian* (1970). In the pre-processing step, the biogenic emissions of isoprene and monoterpenes were calculated following *Guenther et al.* (1993) with respect to the actual meteorological fields of the day from RegCM. Also the temporal disaggregation of the anthropogenic emissions was performed in the preprocessing.

Although chemical transport models usually need a relatively small spin-up time of a few days for initialization, we calculated the full year prior to the decades considered (i.e., 1990, 2040, and 2090). In addition, we ran the period from 1990 to 2001 with RegCM fields driven by the ERA-40 reanalysis (*Uppala et al.*, 2005) for the validation of the model system. The comparison of the ERA-40 run with measurements and with the control run showed a reasonable agreement and will be described in a separate study.

2.2. Emissions

Anthropogenic emissions used in this study are based on the UNECE/EMEP database (http://webdab.emep.int/) for European emissions (*Vestreng et al.*, 2005) for the year 2000. The "expert emissions" are derived from the national totals reported by the individual countries and have been completed and corrected/substituted for the use of dispersion modeling. These data comprise the annual sums of the emissions of NO_x, CO, non-methane hydrocarbons, SO_2, NH_3, fine particles (<2.5 μm), and coarse particles (2.5 μm to 10 μm) on a 50 km × 50 km grid. 11 sectors of anthropogenic activity are distinguished.

For the Pannonean countries Austria, Czech Republic, Hungary, and Slovakia, the EMEP data for the year 2000 are downscaled to a spatial resolution of 5 km × 5 km. An emission inventory for theses countries from the year 1995 (*Winiwarter* and *Zueger*, 1996) is used as database for the spatial distribution of the emissions within the 50 km × 50 km EMEP grid cells.

For every sector the emission model applies different distributions for the month, day of the week, and hour of the day for temporal disaggregation. The disaggregation factors are taken from the inventory by *Winiwarter* and *Zueger* (1996). They are available for the Pannonean countries. For all other countries the disaggregation data for Austria have been used.

The emissions from the inventories must be splitted sector specifically into the speciation of the chemical compounds that corresponds to the chemical mechanisms of the photochemical model. In the case of NO_x it is assumed in all sectors of anthropogenic emissions, that 10% are NO_2 and 90% are NO (in molar percentages). The emissions of non-methane hydrocarbons are disaggregated in accordance with the needs of the chemical mechanism CBM-IV (*Gery et al.*, 1989). This results in specific emissions of the following species, given in CBM-IV notation: PAR (alcane groups), ETH (ethene), OLE (alcene groups), TOL and XYL (aromatics of different reactivity), FORM (formaldehyde), and ALD2 (aldehydes, ketones). The emissions of $PM_{2.5}$ were splitted into organic aerosol (POA), elementary carbon (PEC), and remaining aerosol following the split suggested in the EMEP model (*Simpson et al.*, 2003). In addition, the following species are emitted without chemical disaggregation: CO, SO_2, NH_3, and $PM_{2.5-10}$.

The anthropogenic emissions were not changed between the three decades, although it may be assumed for sure, that changes, mainly in energy supply, both for stationary and mobile sources, will have the most important impact on future air quality. However, there is a large uncertainty about the actual future emissions, even for the next approaching decades, that depends on technical development and energy availability in the future.

2.3. Other input data

Regional photochemical transport models need concentrations of trace species prescribed at the lateral boundaries and the top of the model. They have an influence on the model results when the wind moves air masses from the boundaries into the model. In the calculations described in this study, we assumed clean air conditions at all boundaries, namely 40 ppbv of ozone and very low mixing ratios for all other compounds. This implies that changes of these concentrations in the global background, that may be caused by changes of climate or other conditions, are not covered by this study. In addition, impacts from potential changes in stratosphere/troposphere exchange as well as effects of long range transport of pollutants, which often takes place at tropospheric altitudes above the top of our model grid (*Trickl et al.*, 2003), are not considered here. As stated previously, future changes in land use may also be expected. Such changes might affect atmospheric composition through emissions, including biogenics, and through deposition of compounds. For this parameter also the same data for the present time were used for every decade. The data come along with the preprocessor terrain of the regional mesoscale model MM5 (http://www.mmm.ucar.edu/mm5/). They distinguish 25 land use categories and are based on global data from the United States Geological Survey (USGS).

3. Results

3.1. Daily maxima of ozone in summer

In air quality studies, changes in the daily maximum concentration of ozone are of particular interest, since they allow us to estimate to which extent legal thresholds of ozone may be exceeded in a future climate. At present, following European legislation, the population has to be informed about ozone volume mixing ratios exceeding 90 ppbv. Values above 120 ppbv must lead to further measures.

However, it must be noted that the spatial resolution of the model setup in this study does not allow calculating urban plumes. Instead, only background concentrations are calculated. Therefore, the calculated maxima are expected to be lower than the maxima typically measured. Averaging may also result in lower values than it may be observed in the real world. In the following, seasonal averages of the daily maxima for the decades considered during summer are presented.

Seasonal averages of the daily ozone maxima as calculated for the control decade 1991–2000 for summer (JJA) are displayed in *Fig. 1* (upper left panel). The highest values of more than 60 ppbv are obtained over the Mediterranean Sea. A latitudinal gradient can be observed with the lowest values in the north, and the highest values in the south. In general, this corresponds to the observed behavior of ozone over Europe at the present time.

The upper right panel of *Fig. 1* shows the difference in the decadal average of the daily ozone maxima between the mid-century period and the control run. All differences are small. An increase below 2.5 ppbv can be observed over the southeast part of Europe, stretching as far west as Italy and southern Germany. For most of the rest of the model domain over Europe, a slight decrease of the ozone maxima occurs. In a belt from southern England along the North Sea coast to southern Scandinavia, this decrease is somewhat stronger, but still below 5 ppbv.

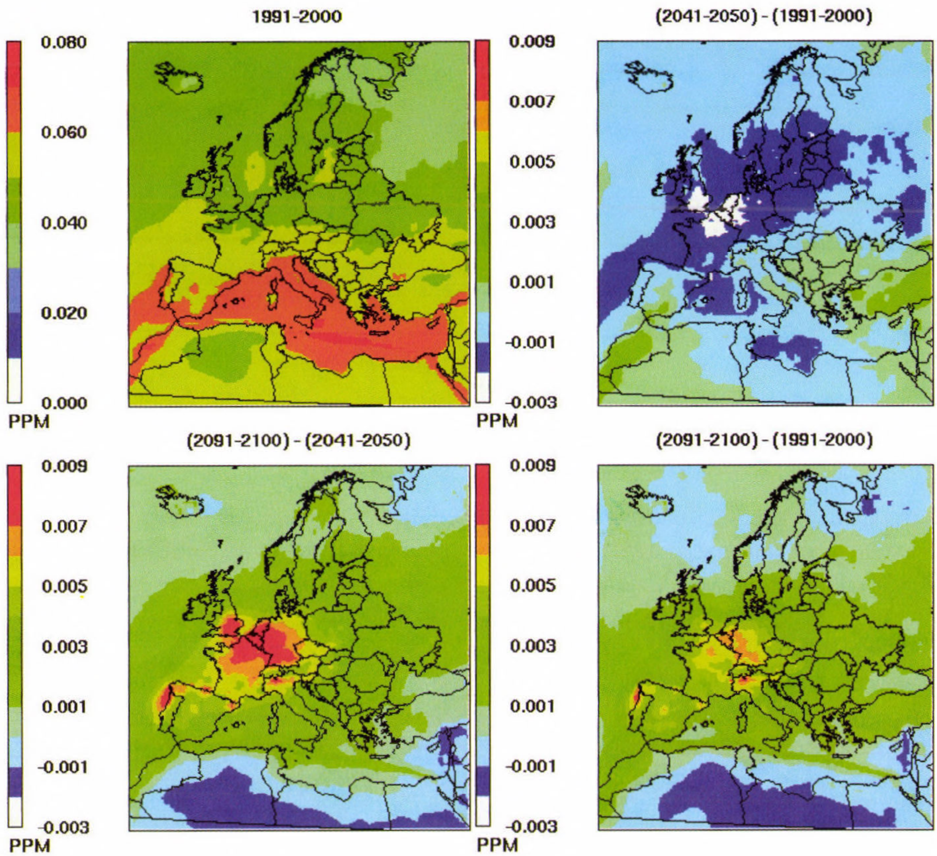

Fig. 1. Average of the daily maxima of ozone volume mixing ratio in summer (JJA) from the control decade 1991–2000 (upper left), and differences of the maximum ozone volume mixing ratios in summer between the calculated decades: first half-century (upper right), second half-century (lower left), and whole century (lower right).

Between the mid-century and end-century decades, a much stronger increase of the ozone maxima occurs. The highest increase is located over southern England, northern France, the Benelux countries, and western Germany reaching about 10 ppbv. However, with the exception of Africa, the eastern Mediterranean, and northern Russia, an increase of ozone is calculated all over the model domain.

The difference between the results of the end-century and control runs showing the development of the ozone maxima within 100 years is displayed in the lower right panel of *Fig. 1*. Due to the stronger increase in the second half of the 21st century, the decrease of ozone in the first half over wide parts of Europe is compensated. The highest change occurs over northern France, Belgium, and western Germany, as well as over the Po valley in Italy. These regions have the highest emissions of ozone precursors at the present time. Since the anthropogenic emissions were not changed between the decades, this emission pattern persists throughout the century.

3.2. Daily maxima of ozone in other seasons

In the other seasons the averaged daily maxima of ozone do not change as strongly as in summer. In spring (MAM) the ozone values increase from the control decade to the end-century decade by about 3 ppbv over most parts of Europe except for Scandinavia and the British Isles, where the increase is lower or even a slight decrease was calculated. The spring increase is of the same amount as in summer, except for those parts of western Europe that show a stronger summer increase. As an illustration, *Fig. 2* displays the change during the whole century in spring and autumn.

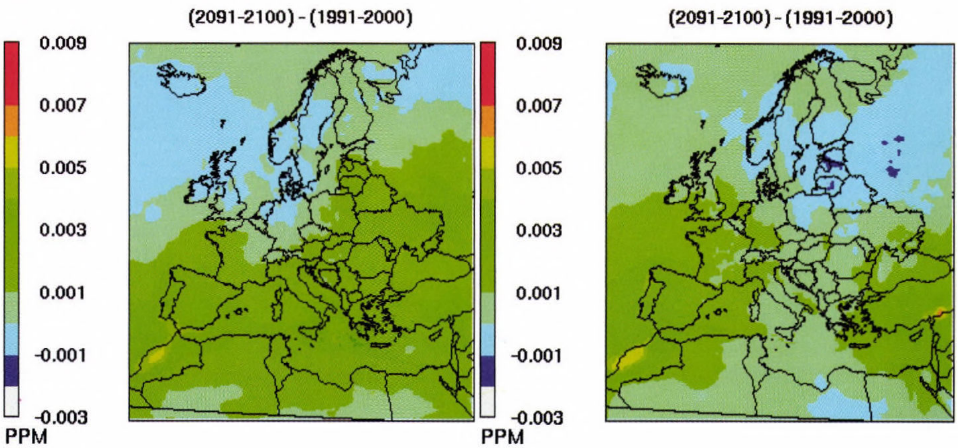

Fig. 2. Differences of the average daily maxima of ozone volume mixing ratio in spring (MAM, left) and autumn (SON, right) during the whole century.

In autumn (SON) the average of the daily ozone maxima decreases over most of Europe in the first half of the 21st century and increases in the second half; each change is approximately 3 ppbv. For the whole century this results in a slightly stronger increase over western Europe than over the central and eastern regions. Winter (DJF) shows the smallest changes. In contrast to the other seasons, a decrease of ozone occurs in winter in the second half of the century in most land-covered parts of the model domain, while other regions show a small increase between the control decade and the mid-century decade.

Since the highest concentrations of ozone occur in summer causing perturbations of the air quality by exceeding legal thresholds, and since the highest alterations due to climate change in these calculations also occur in summer, in the following only the changes in summer will be further considered in this study.

3.3. AOT40

Accumulated ozone exposure values over a certain threshold (AOT) are common measures for the ozone impact. In this study we compare AOT40 (accumulated ozone over a threshold of 40 ppbv) for the period from April to September, which is considered as a measure for the impact of ozone on forests. The sum of the differences between the hourly mean ozone concentration (in ppb) and 40 ppb for each hour when the concentration exceeds 40 ppb, accumulated between 8:00 and 20:00 hours during the period is calculated. As a long-term objective for the protection of forests, a maximum value of 10000 ppbv h is considered. (*European Communities*, 2002).

The upper left panel of *Fig. 3* shows the average AOT40 data as they were calculated for the control period 1991–2000. Only in northern Europe the long-term objective is not exceeded. The highest values can be found over the Mediterranean Sea. In the first half of the 21st century, AOT 40 goes down over most of Europe, except of the Iberian Peninsula and southeast Europe (upper right panel), while there is a strong increase over most of Europe in the second half of the century (lower left panel). The lower right panel shows that during the whole 21st century, AOT40 values will go up over the whole of Europe with the highest increase over the Iberian Peninsula and the Alps.

Similar results were obtained for other quantities describing the exposure to elevated ozone concentrations like AOT40 (May–July), which is considered as a measure for the exposure of agricultural plants during the growing period, or AOT60, which measures the exposure of humans. Also average ozone concentrations show a small change during the first half of the 21st century and a strong increase in the second half, with stronger increases in the south part of Europe than in the north.

3.4. Temperature

As an indicator for the changing climate, the changes of the temperature in the lowest model level are shown, as they were taken from the RegCM results, which were input data to the photochemical model CAMx. The upper left panel of *Fig. 4* shows the average summer temperature from the control period 1991–2000 with the expected north-south gradient.

The changes in average temperature until the mid-century decade 2041–2050 are less than 1 degree over most of Europe except for the very northern areas as well as southern Spain, Sicily, and southern Greece, where an increase between 1 and 2 degrees occurs, as it is shown in the upper right panel. Over England and northwestern France there is even a decrease of the average temperature. In the second half of the 21st century a much stronger increase occurs, displayed in the lower left panel, amounting to 1 to 2 degrees in northern Europe, up to 3 degrees in Germany and eastern Europe, up to 4 degrees over France and Italy, and even more over the Iberian peninsula.

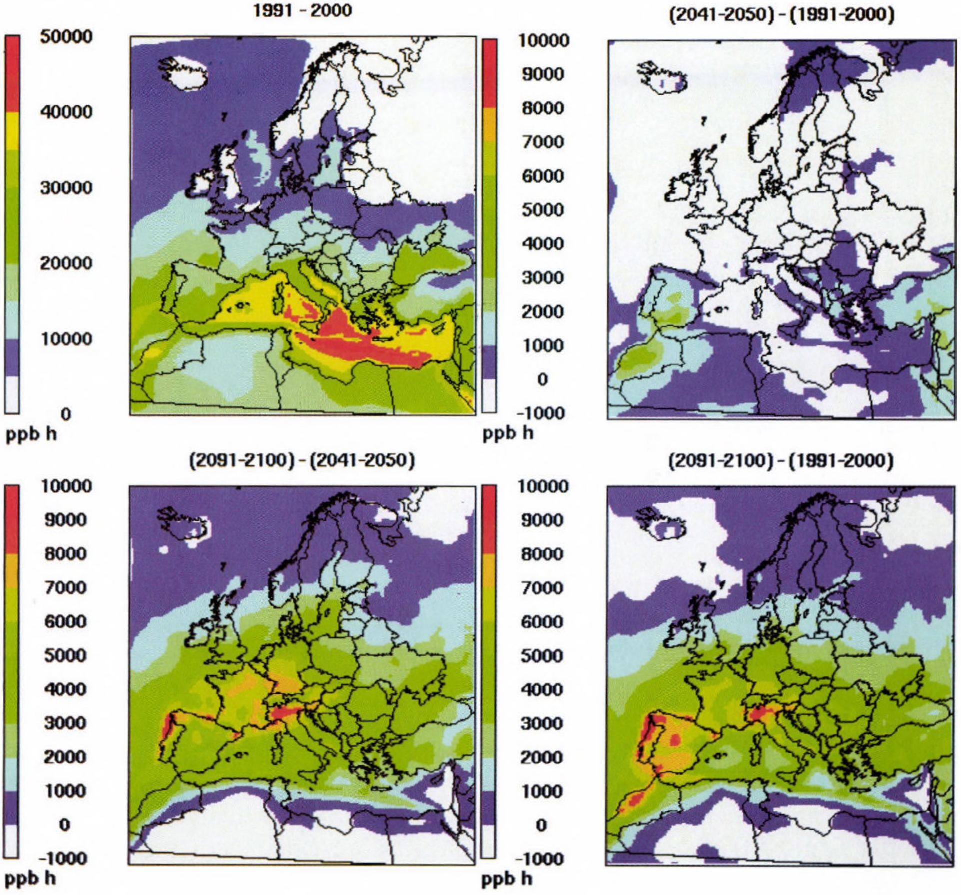

Fig 3. AOT40 (accumulated ozone over a threshold of 40 ppbv) from April to September in the control decade 1991–2000 (upper left), and differences of AOT40 from April to September between the calculated decades: first half-century (upper right), second half-century (lower left), and whole century (lower right).

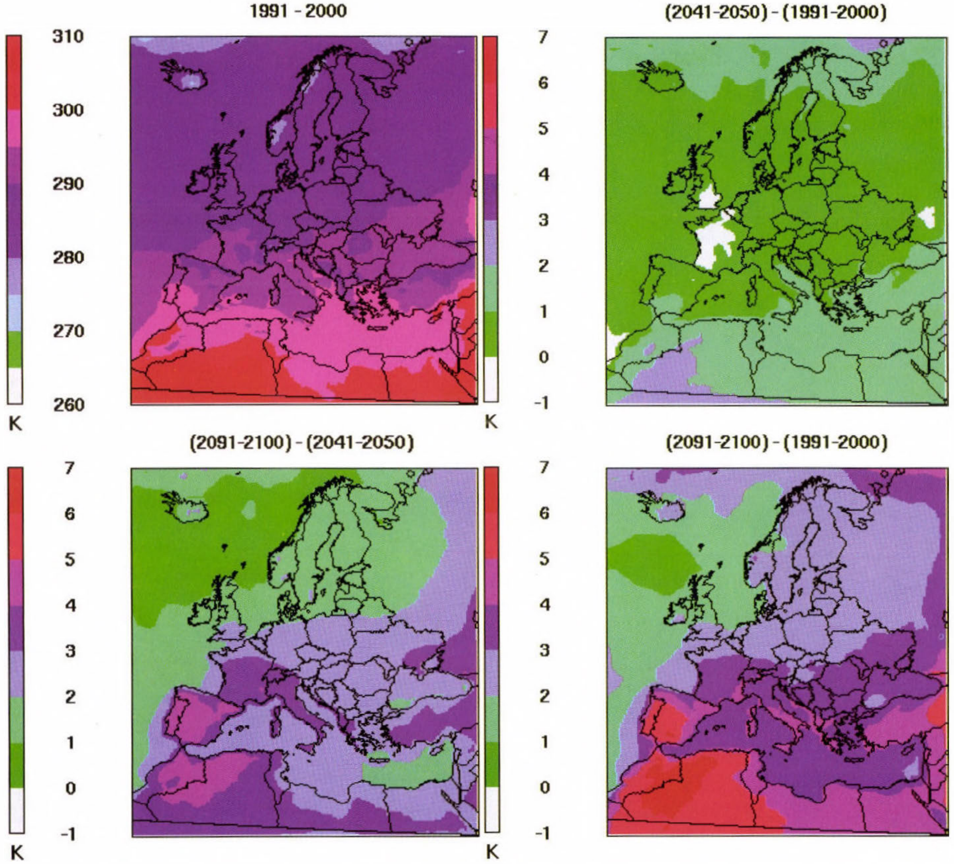

Fig. 4. Average temperature in the lowest model level in summer (JJA) in the control decade 1991–2000 (upper left), and differences of the average temperatures in summer between the calculated decades: first half-century (upper right), second half-century (lower left), and whole century (lower right).

3.5. Cloud optical depth

Besides temperature, photochemical activity is strongly influenced by the amount of radiation, which drives the formation of radicals and enhances the production of biogenic hydrocarbons. These emissions act as precursors in ozone formation along with the anthropogenic emissions of hydrocarbons and nitrogen oxides. In CAMx the photolysis rates are calculated from a look-up table that contains clear sky photolysis rates at various solar zenith angles, altitudes, total ozone columns, values for the surface albedo, and atmospheric turbidity. The effect of clouds is treated based upon the RADM approach (*Chang et al.*, 1987), in which the cloud optical depth is used to scale down the photolysis rates for layers within or below clouds to account for UV attenuation, or to scale up the rates for layers above clouds to account for UV reflection. The cloud optical depth is calculated by an empirical expression with the preprocessor from the actual cloud water mixing ratio.

As a qualitative measure of the attenuation of radiation, *Fig. 5* shows the average cloud optical depth of the control period (upper left panel) during summer. The highest values in the model domain occur over the Atlantic Ocean, and the lowest values are observed over the Mediterranean Sea. During the first half of the 21st century there is an increase all over Europe. The highest rise occurs over the sea (Atlantic Ocean, North Sea, Baltic Sea), while over southern Europe the increase is small (upper right panel). This increase in the cloud optical depth leads to a reduction in photochemically active radiation.

In the second half of the century the cloud optical depth decreases all over Europe. With the exception of northern Europe, this decrease compensates the increase in the first half (lower right panel). This net effect is that the photochemically active radiation becomes stronger.

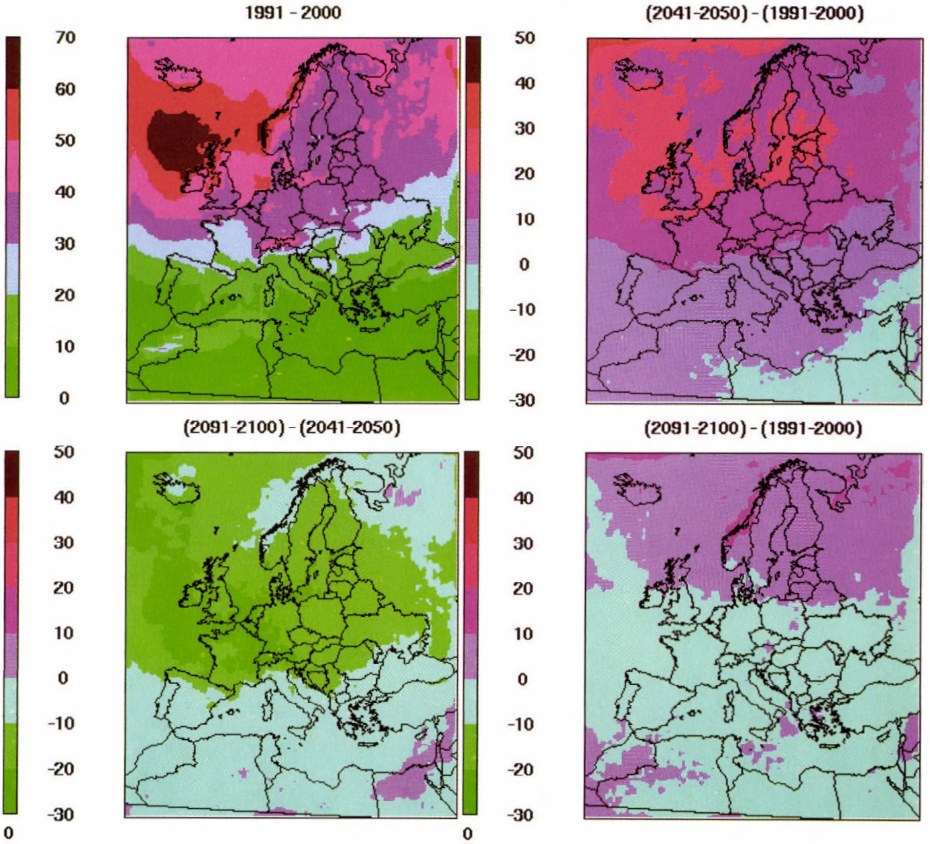

Fig. 5. Average cloud optical depth in the lowest model level in summer (JJA) in the control decade 1991–2000 (upper left), and differences of the average cloud optical depths in summer between the calculated decades: first half-century (upper right), second half-century (lower left), and whole century (lower right).

3.6. *Isoprene*

Higher temperatures and stronger radiation both support the emission of biogenic hydrocarbons. Isoprene and monoterpenes are the only ozone precursors, with changing emissions in the decades calculated in this study. The change of the volume mixing ratio of isoprene is displayed in *Fig. 6*. The upper left panel shows the summer average of isoprene during the control period. Since the lifetime of isoprene amounts to only a few hours or even less, noteworthy concentrations occur over the land areas only. The highest values can be found over Portugal and the Balkan. Until the decade from 2041 to 2050 the values increase slightly over most of the model domain. Even over the sea a small increase is plotted. The increase continues until the end-century decade. During this time span there is a greater increase of the isoprene concentration over the areas that had the highest abundance already.

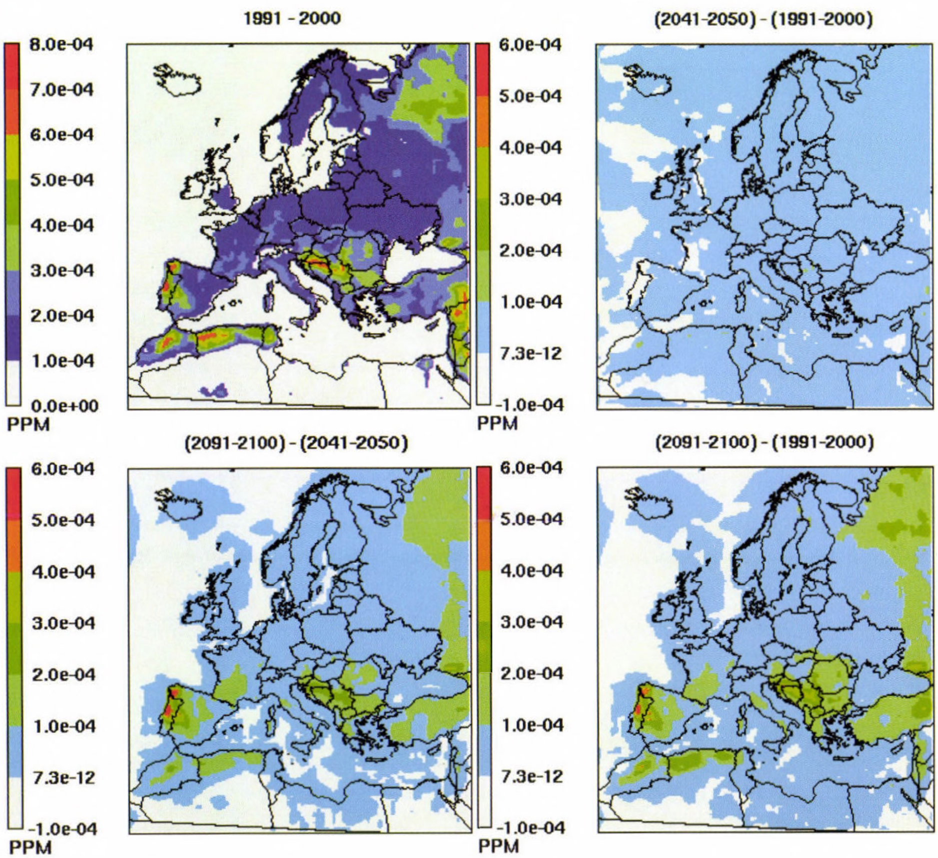

Fig. 6. Average volume mixing ratio of isoprene in the lowest model level in summer (JJA) in the control decade 1991–2000 (upper left), and differences of the average volume mixing ratios in summer between the calculated decades: first half-century (upper right), second half-century (lower left), and whole century (lower right).

4. *Discussion*

Photochemical model calculations, which are driven by meteorological fields from climate scenario runs with a regional climate model, show an increase of ozone formation concurrent with climate change. In the second half of the 21st century, the increase of the ozone concentration is much stronger than in the first half, coinciding with a larger increase in average temperature and a decrease of the average cloud optical depth.

Since ozone is a secondary pollutant that is formed in the atmosphere, its abundance depends on the availability of sufficient ozone precursors. In addition, the right conditions must be present, including the presence of high temperatures, strong solar radiation, and stagnant winds. Biogenic emissions were the only variable ozone precursors in this study, and their emission in turn depends on temperature and radiation in the model. Therefore, it follows that ozone should increase mostly where the highest increases of temperature and radiation occur.

By comparing the results for the decade 2041–2050 with the control period 1991–2000, the changes projected for the first half of the 21st century can be seen. A small increase of temperature occurs over most parts of Europe. On the other hand, there is also an increase in the cloud optical depth, which, therefore, counteracts ozone formation due to less radiation. This results in only a small increase of the averaged daily maxima of ozone in southeastern Europe, where the effect of temperature change seems to outweigh the effect of radiation. In northern and western Europe the opposite occurs and the average daily maxima of ozone are reduced. Similar results of increasing and decreasing values are obtained for AOT40 (Apr–Sep) as well as for other ozone measures, which are not shown.

In the second half of the 21st century, the temperature increase in the input data is much stronger, and the radiation increases due to a decrease of the cloud optical depth. Therefore the calculated increase of ozone in all parts of Europe is also much stronger in the later half of the 21st century

The highest changes of ozone occur in summer, the season that shows the highest ozone concentrations. Interestingly, these future increases in ozone occur where the highest emissions of ozone precursors are present, not where the highest temperature increases occur. From the increase of the averaged daily maxima of ozone it can be concluded, that the ozone concentration would exceed present legal thresholds in the future more often under the assumptions of unchanged anthropogenic emissions of ozone precursors. The long-term objective for AOT40 (Apr–Sep) of 10000 ppbv h will also not be maintained under these conditions.

An increase of biogenic hydrocarbon emissions caused by higher temperatures and stronger radiation certainly supports ozone formation. However, this effect should be treated with caution, since the meteorological effects also may lead to changes in land use, which in turn affects the intensity of emissions. In addition, there are indications that the production of isoprene by forest ecosystems may be reduced under conditions of elevated CO_2 concentrations (*Rosenstiel et al.*, 2003, *Monson et al,* 2007), which is the main driving force for the projected climate change. Such feedbacks were not considered in this study and land use patterns were kept constant over all decades.

Furthermore, areas with the strongest increase of biogenic emissions must not be, by all means, the areas with the strongest ozone increase, since NO_x must also be available for ozone formation. For example, the Balkan area shows a strong increase of isoprene until the 2091–2100 decade (*Fig. 6*), while the increase of ozone in that area is not exceptionally strong (*Fig. 1* and *Fig. 3*). *Forkel* and *Knoche* (2007) show similar results for this area and explain them with the lack of NO_x.

The concentration of ozone may also change due to alterations of the patterns of horizontal atmospheric transport within the model domain. Such phenomena have not been investigated in this study. On the other hand, effects of vertical transport were excluded from this study, since constant clean air conditions have been assumed at the top of the model.

The coarse grid resolution of 50 km in the CAMx calculation implies, that this is a study for background concentrations. The highest concentrations of ozone are normally observed within urban plumes, while urban areas, on the other hand, usually show a strong reduction of ozone during nighttime due to destruction by primary emissions of NO. These features are not resolved with the applied model grid. In addition, the 50 km resolution of the used emission inventory causes an instantaneous mixing of emitted ozone precursors. This also prevents the formation of high ozone concentrations as well as local destruction. Therefore, extreme high and low ozone values may not be expected in the model results. Within the project CECILIA, air quality calculation with a higher spatial resolution will be performed at a later stage for smaller model domains.

The results of this study agree well with results from other studies, although they may be compared only qualitatively, since other studies use different greenhouse gas scenarios and different time periods are considered. *Forkel* and *Knoche* (2007) calculated the 2030s-decade as climate projection, and also found an increase of ozone over Europe. *Hedegaard et al.* (2008) performed their calculations for the same decades as in this study, but they used the A2 scenario and a coarser model resolution. However, they did not find the distinction between small changes in the first half and strong changes in the second half of the 21st century that was found in this work. This difference is likely to be caused by the different GCM boundary conditions. *Meleux et al.* (2007) looked at time slices of 30 years, in contrast to 10 years in the other studies. However, their qualitative result is very similar. Nonetheless, the fact, that different models applied under partly different assumptions lead to qualitatively similar results, shows some robustness of the message that the projected climate change would lead to enhanced ozone formation if anthropogenic emissions would be kept unchanged.

5. Summary and conclusions

Regional photochemical model simulations were carried out with the model CAMx. The model domain covered Europe with a spatial resolution of 50 km. Three decades were calculated, namely 1991–2000, 2041–2050, and 2091–2100, driven by a climate change simulation of the model RegCM. These in turn were driven by the global model simulation of the ECHAM5 model under the SRES-A1B-greenhouse gas scenario.

Of the many species calculated by the photochemical model, this study mainly examined ozone concentrations during summer due to its adverse effects on human health and vegetation. Ozone levels are projected to increase over Europe during the 21sth century. The increase will be stronger in the second half of the century; in the first half a decrease in northern parts of Europe is projected.

The projected ozone increase must be attributed to more frequent meteorological conditions that promote ozone formation like high temperature, strong solar radiation, and stagnant flow conditions. In addition, increasing concentration of biogenic hydrocarbons calculated with respect to the meteorological input data, which in turn are dependent on the temperature and the available radiation, may also be a factor in the projected ozone increases.

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BOOK REVIEW

C. Gualtieri and *D.T. Mihailović* (eds.): **Fluid Mechanics of Environmental Interfaces**. Taylor and Francis, London, 2008, 348 pages, 11 chapters.

C. Gualtieri and *D.T. Mihailović* assembled an international team of 16 authors with the idea to condense into a textbook an overview of fluid mechanical processes in the environmental interfaces. The book is divided into three parts with an introductory chapter. The introductory chapter, written by *B. Cushman-Roisin* and the editors, focuses on the importance of turbulence and stratification in environmental systems. Furthermore, it touches on the main differences between engineering fluid mechanics, geophysical fluid dynamics, and environmental fluid mechanics.

The first part is dedicated to the processes at atmospheric interfaces. Starting from the theory of atmospheric dispersion and modeling of dispersion of passive substance, the authors guide the reader through the concepts of the modeling of momentum, heat, and mass flux exchange between heterogeneous land surfaces, sea surface, as well as the atmosphere. The part is closed with description of desert dust transport.

Part two is devoted to the fluid mechanical processes at water interfaces. This part reviews the theory and numerical simulation of gas transfer at unshared free surfaces important for water quality in aquatic systems. It also elaborates basic mechanisms, analytical solutions of advective diffusion of air bubbles in turbulent water flows and analyses structure of the bubbly flow.

The final part covers processes at the interfaces between atmosphere or water and biotic systems. Opening with a very detailed description of transport processes and parameterizations in the soil-vegetation-lower atmosphere system, the third part deals with mechanical effects of forest canopy, rigid submerged vegetation in open channels.

Assuming undergraduate knowledge of fluid mechanics and environmental physics, each chapter is written easy to understand. The considerable drawback of the book, which can confuse an inexperienced reader, is the usage of non-uniform formula type by different authors. Unfortunately, the book contains some grayscale contour graphs and low resolution pictures taken from the internet which do not provide necessary information. In contrast, the high resolution full color illustrations are very impressive.

The book represents a very good compilation of modern theoretical and experimental approaches in fluid mechanical processes at environmental interfaces. It is especially useful for students, engineers, and scientists working in the fields of environmental engineering and sciences as well as applied mathematics.

Á. Bordás

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