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

Gabriella Szépszó[*] and **András Horányi**

Hungarian Meteorological Service,
P.O. Box 38, H-1525 Budapest, Hungary
E-mails: szepszo.g@met.hu, horanyi.a@met.hu

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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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[*] Corresponding author

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.

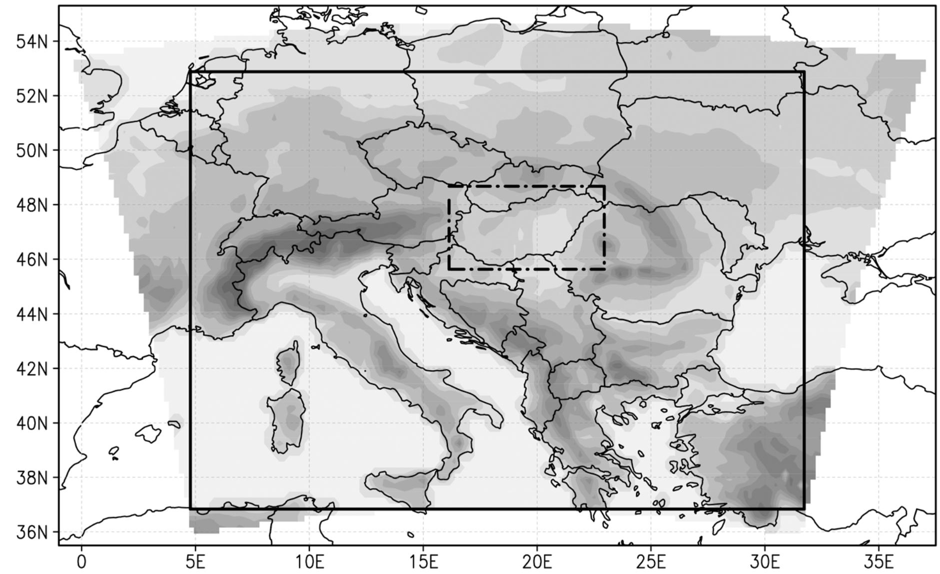

Fig. 1. Orography of the REMO domain used for the long transient climate change simulation (1951–2050). The domain consists of 101×81 gridpoints and its horizontal resolution is approximately 25 km (exactly 0.22 degree). The large (solid) rectangle represents the evaluation domain with respect to the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

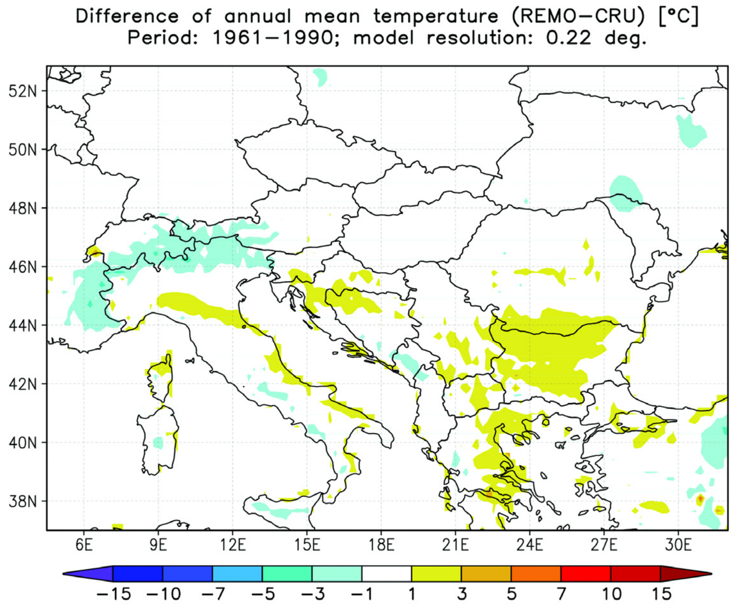

Fig. 2. Difference (in ºC) of the annual mean (2-meter) temperature between the model results and the 10-minute resolution CRU dataset for the period of 1961–1990. The intercomparison was carried out on the 0.22 degree resolution re-rotated model grid.

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.

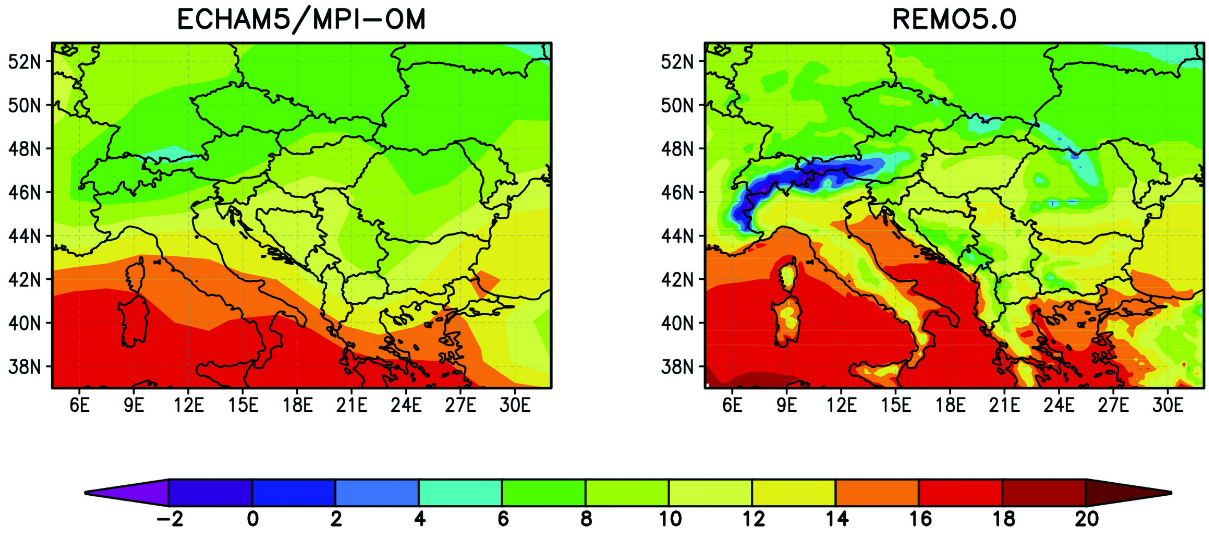

Fig. 3. The annual mean (2-meter) temperature (in ºC) in the results of ECHAM5/MPI-OM global model and ECHAM5/MPI-OM-driven REMO5.0 regional model for 1961–1990. The maps indicate the original model resolutions.

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.

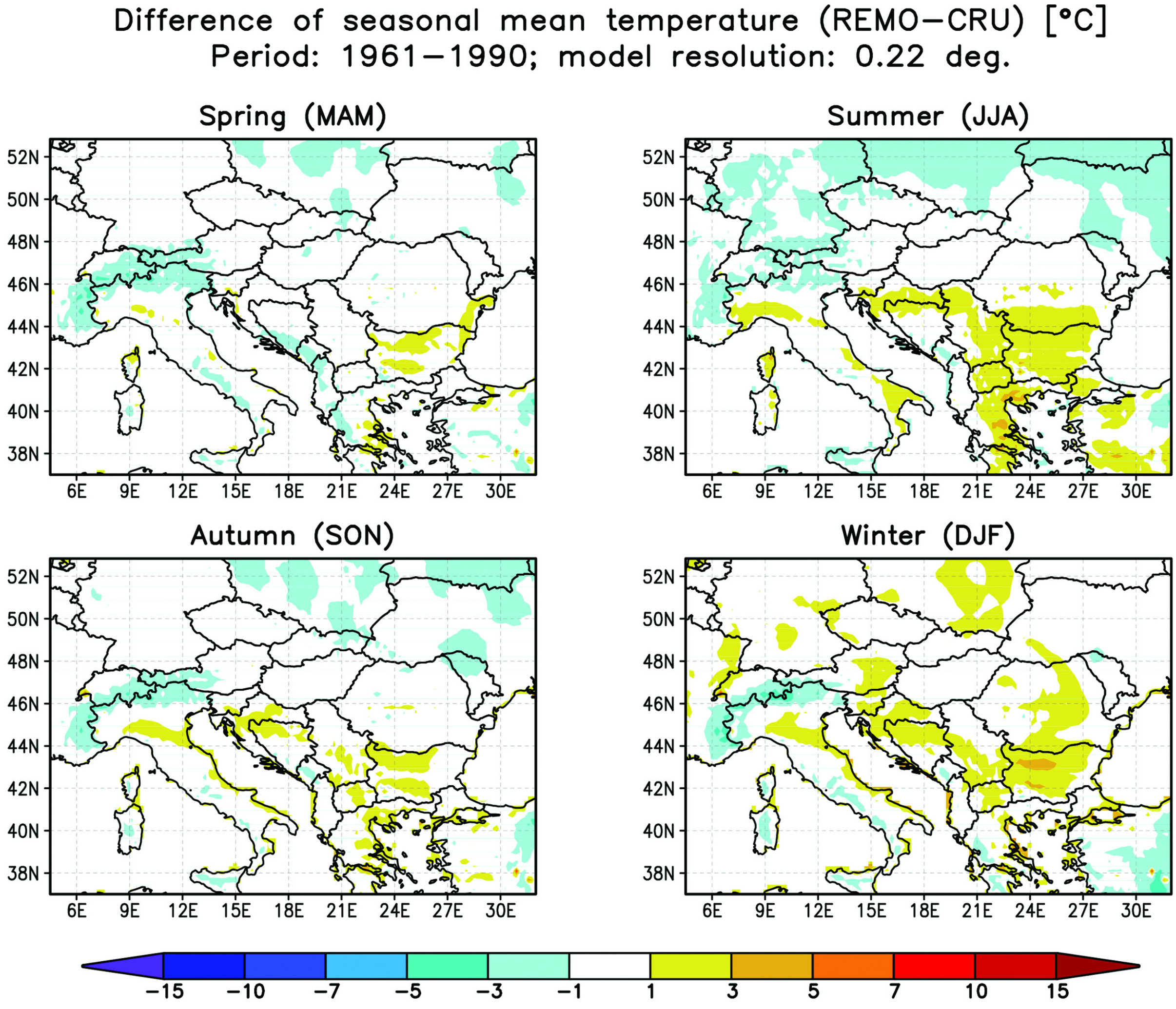

Fig. 4. Difference (in ºC) of the seasonal mean (2-meter) temperature between the model results and the 10-minute resolution CRU dataset for the period of 1961–1990 The intercomparison was carried out on the 0.22 degree resolution re-rotated model grid.

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 ºC. 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 ºC. 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 ºC). 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 ºC interval in general, however, in particular the errors occur mostly between –1 and 1 ºC 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 [ºC]					**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 ºC. 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 [^{o}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.

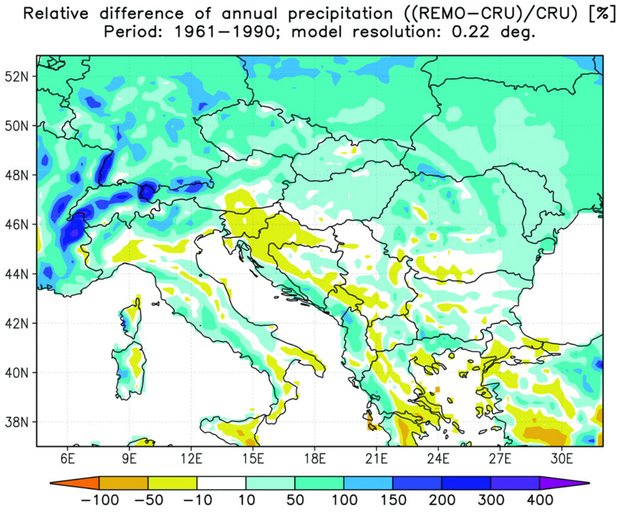

Fig. 5. Relative difference (in percentage) of the annual precipitation between the model results and the 10-minute resolution CRU dataset (reference: CRU dataset) for the period of 1961–1990. The intercomparison was carried out on the 0.22 degree resolution re-rotated model grid.

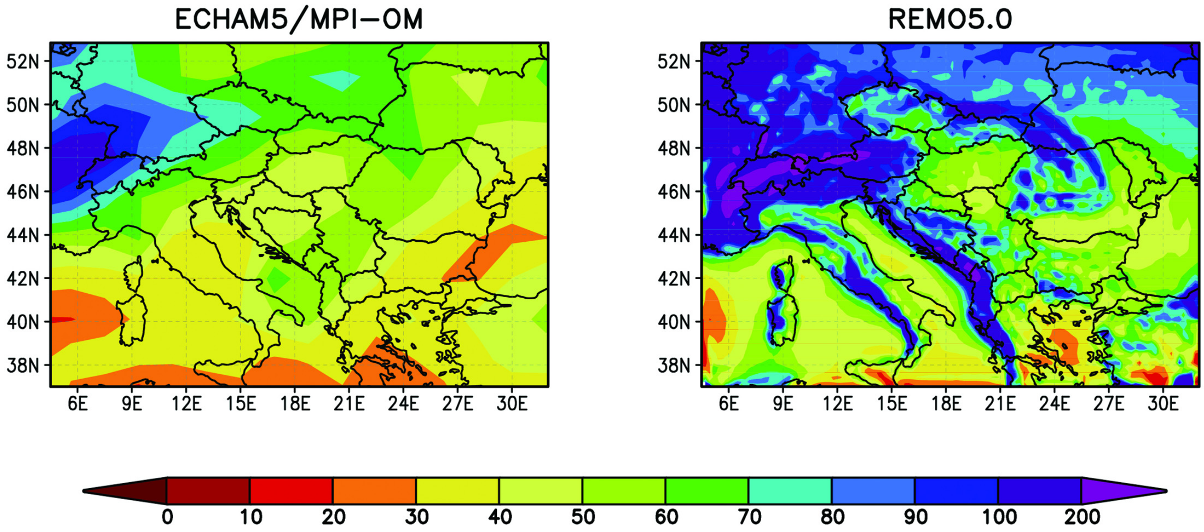

Fig. 6. The annual mean precipitation (in mm/month) in the results of ECHAM5/MPI-OM global model and REMO5.0 regional model for 1961–1990. The maps indicate the original model resolutions.

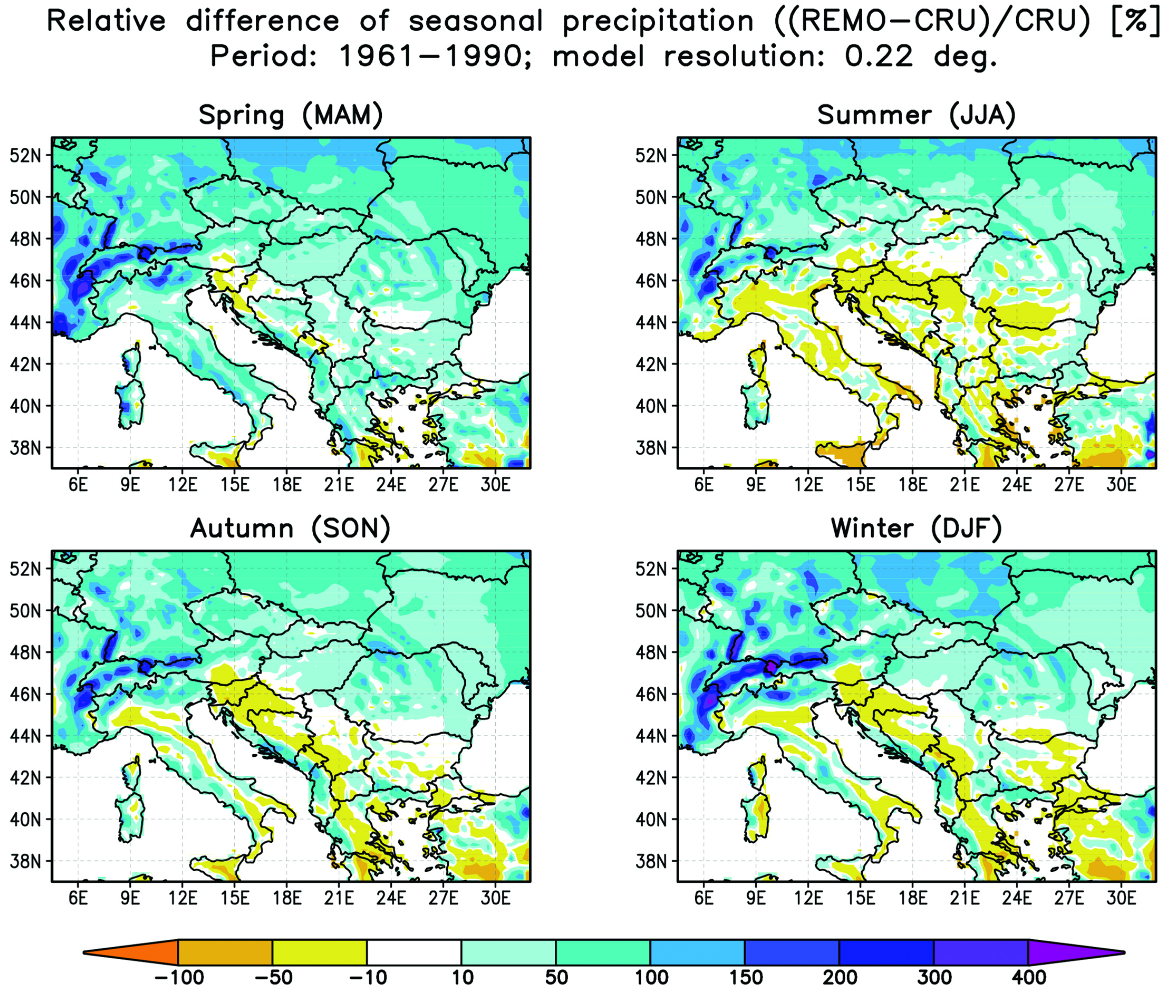

Fig. 7. Relative difference (in %) of the seasonal precipitation between the model results and the 10-minute resolution CRU dataset (reference: CRU dataset) for the period of 1961–1990. The intercomparison was carried out on the 0.22 degree resolution re-rotated model grid.

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.

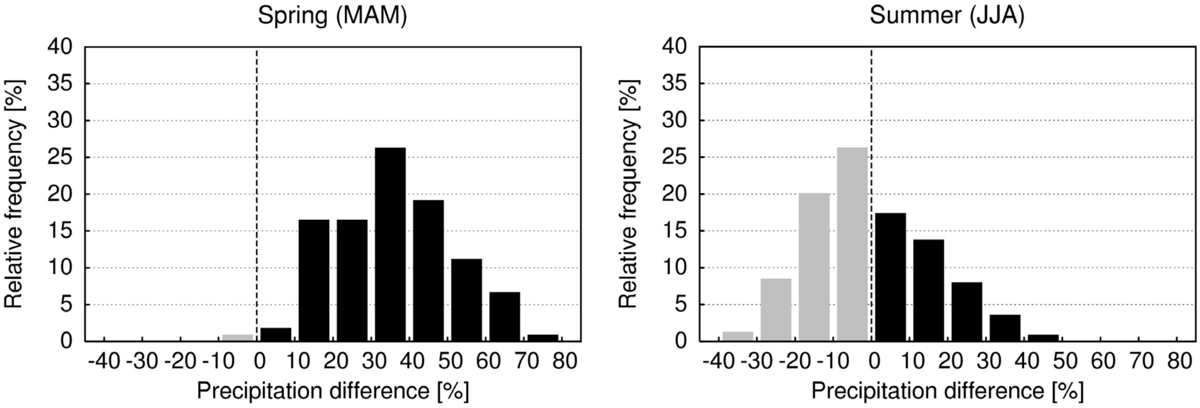

Fig. 8. Discrete density function (in percentage) of the seasonal relative departures (in percentage) for precipitation between the model results and the gridded Hungarian dataset over Hungary for the period of 1961–1990. The dashed line represents the value of 0 percent separating the ranges of over-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

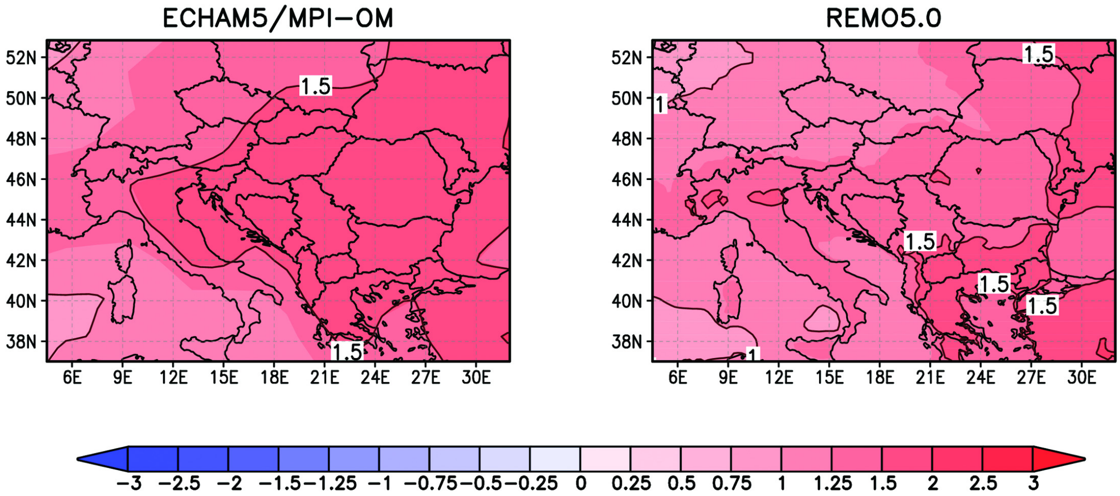

Fig. 9. Change (in ºC) of the annual mean (2-meter) temperature projected by the global ECHAM5/MPI-OM coupled model system and by REMO5.0 for the period of 2021–2050 with respect to the period of 1961–1990.

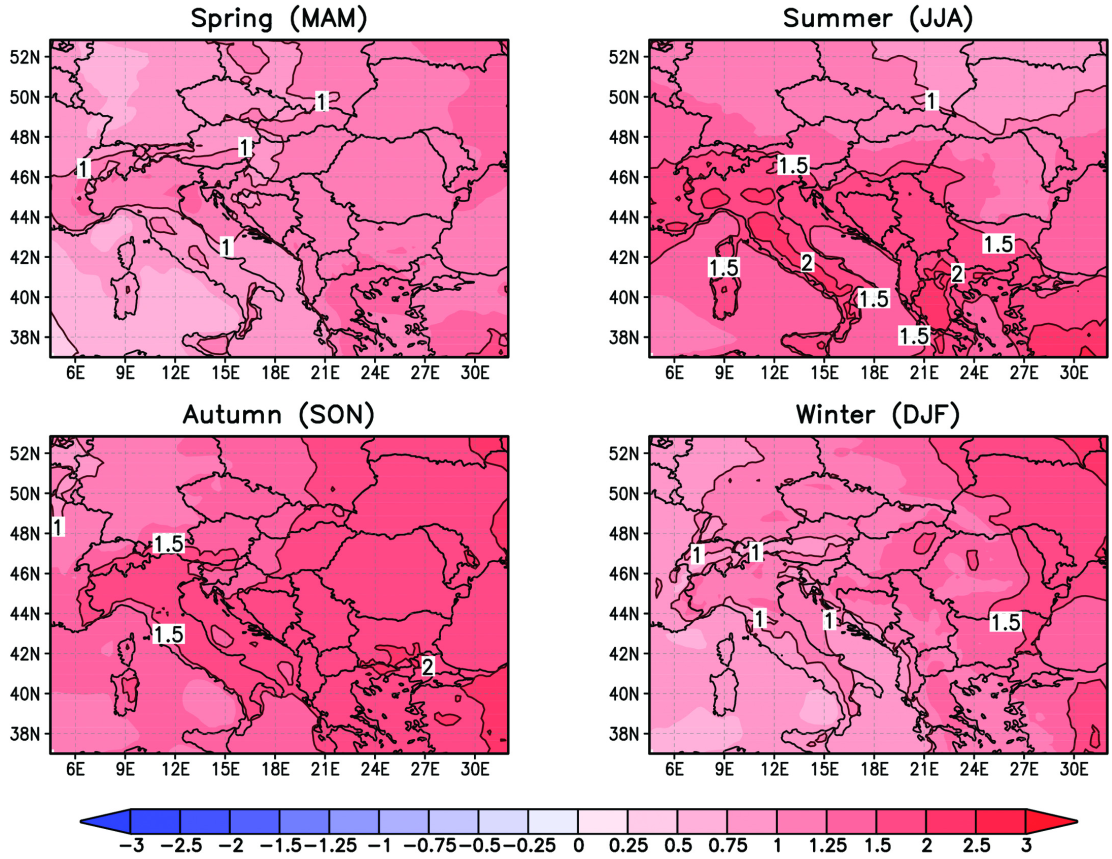

Fig. 10. Change (in ºC) of the seasonal mean (2-meter) temperature projected by REMO5.0 for the period of 2021–2050 with respect to the period of 1961–1990.

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 ºC, while over the northern (cooler) part of the continent, the increase remains between 1 and 1.5 ºC (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 ºC change over Hungary, whereas the global model covers the interval of 1.75–2.5 ºC (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 ºC) 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 ºC 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 ºC in annual mean, and with 1.1, 1.4, 1.6, 1.3 ºC 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.

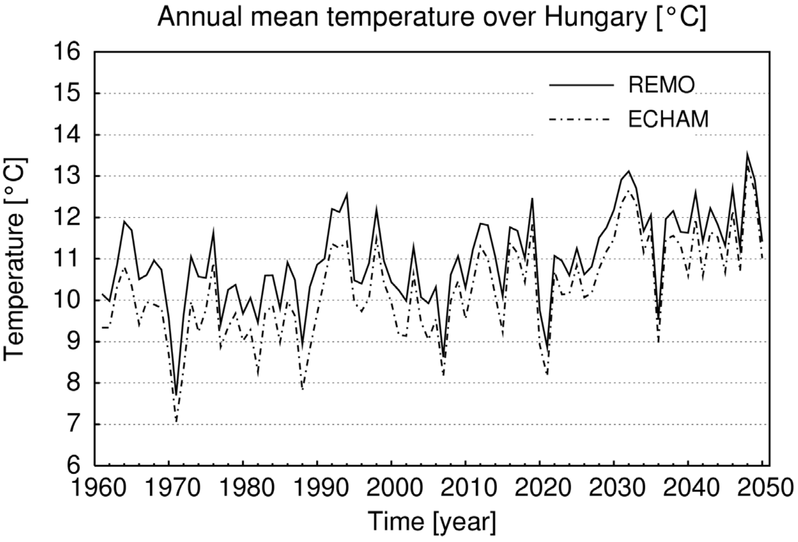

Fig. 11. The annual mean (2-meter) temperature in the results of ECHAM5/MPI-OM global model (chained curve) and ECHAM5/MPI-OM-driven REMO5.0 regional model (solid curve) focused on Hungary for the period 1961–2050.

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 ºC 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 ºC, then for the future this departure decreases to approximately 0.5 ºC (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.

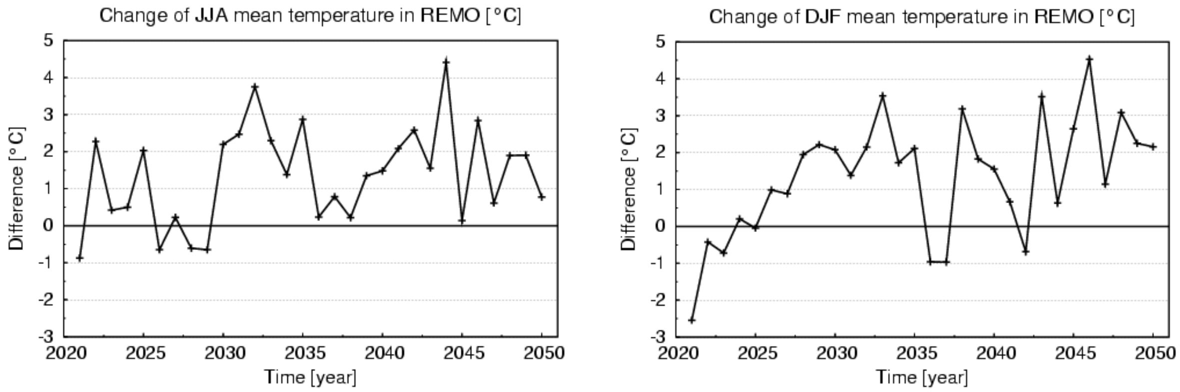

Fig. 12. Evolution of the seasonal (2-meter) temperature change over Hungary projected by REMO5.0 for the period of 2021–2050 with respect to the period of 1961–1990 (left: summer, right: winter).

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.

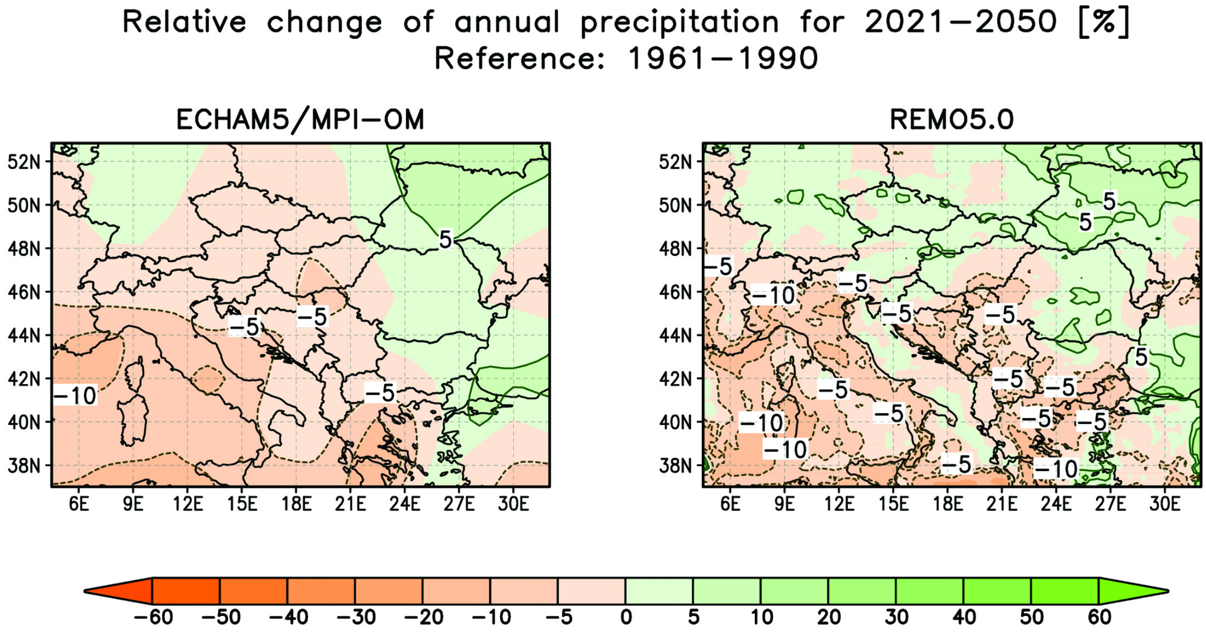

Fig. 13. Relative change (in percentage) of the annual mean precipitation projected by the global ECHAM5/MPI-OM coupled model system and by REMO5.0 for the period of 2021–2050 with respect to the period of 1961–1990.

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.

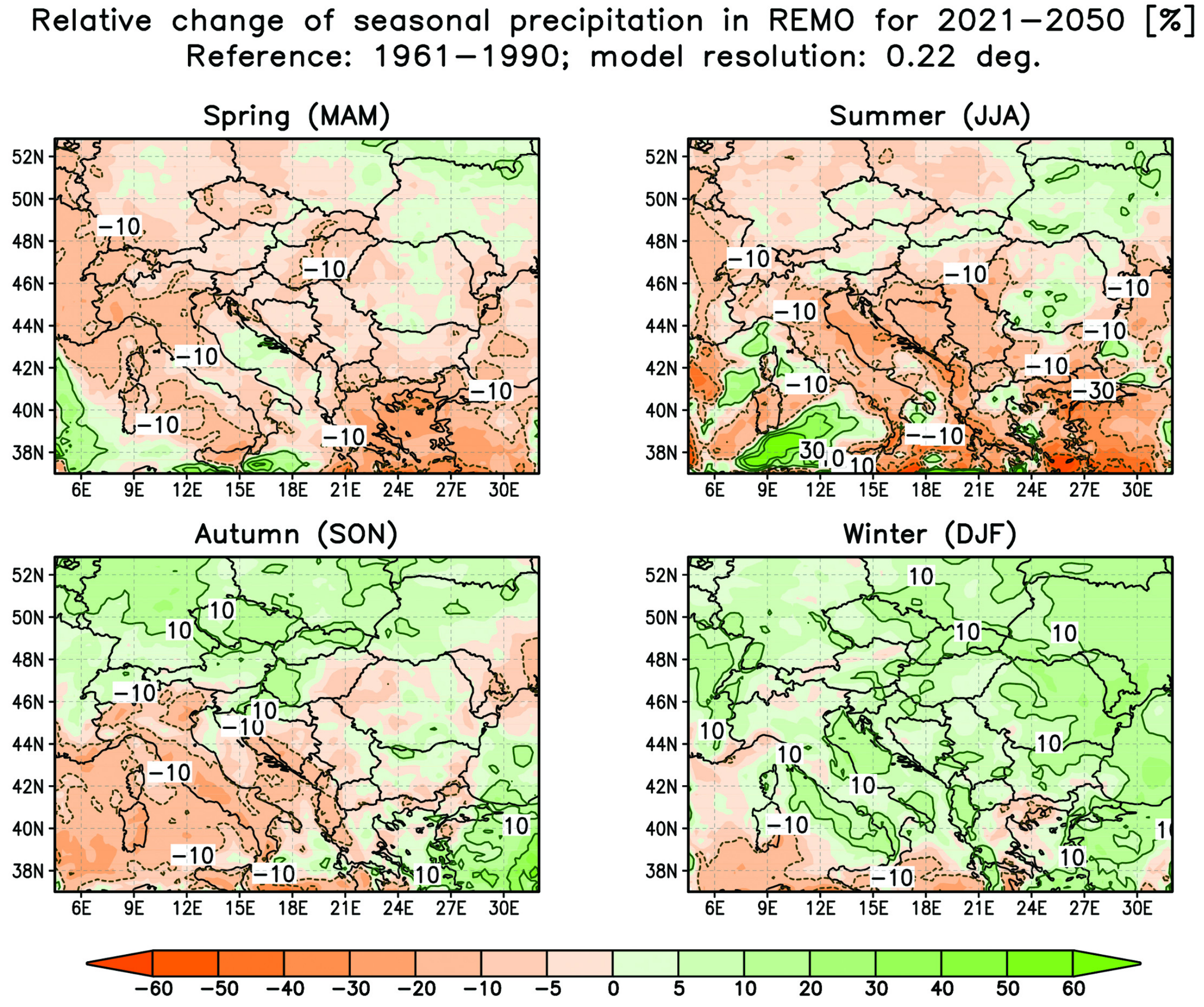

Fig. 14. Relative change (in percentage) of the seasonal mean precipitation projected by REMO5.0 for the period of 2021–2050 with respect to the period of 1961–1990.

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).

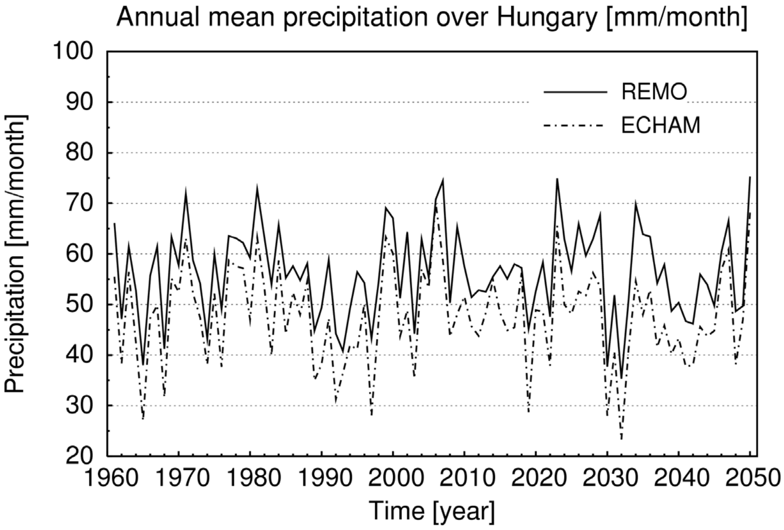

Fig. 15. The annual mean precipitation in the results of ECHAM5/MPI-OM global model (chained curve) and ECHAM5/MPI-OM-driven REMO5.0 regional model (solid curve) focused on Hungary for the period 1961–2050.

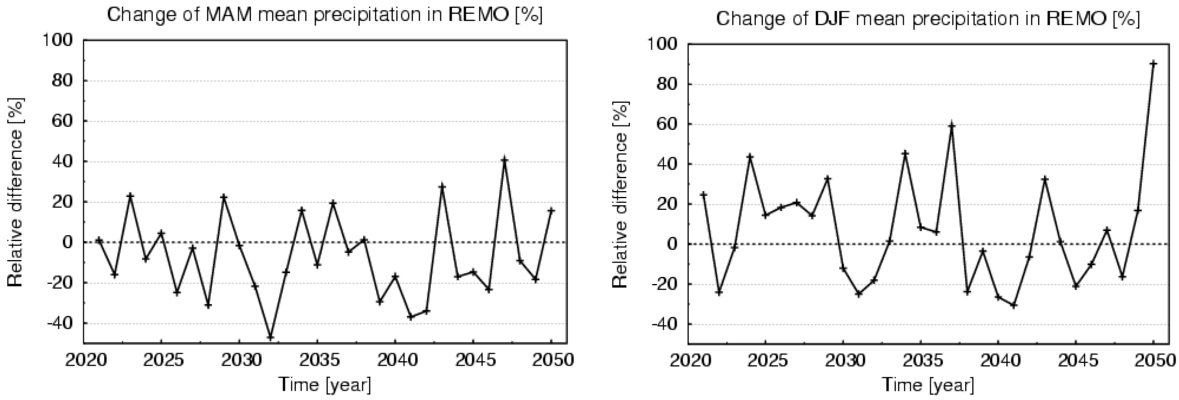

Fig. 16. Evolution of the relative seasonal precipitation change over Hungary projected by REMO5.0 for the period of 2021–2050 with respect to the period of 1961–1990 (left: spring, right: winter).

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 ºC in every season, with the smallest values (1.1 ºC) in spring and largest ones (1.6 ºC) 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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References

Christensen, J.H., 2005: Prediction of Regional scenarios and Uncertainties for Defining European Climate change risks and Effects. *Final Report.* Danish Meteorological Institute, Copenhagen. http://prudence.dmi.dk/public/publications/PRUDENCE%20Final%20report.pdf

Csima, G., 2008: Validation of the ALADIN-CLIMATE regional climate model at the HMS. *Geophys. Res. Abstracts 10,* 1607-7962/gra/EGU2008-A-07728, European Geosciences Union General Assembly 2008, Vienna, Austria.

Cubasch, U., Waszkewitz, J., Hegerl, G., and *Perlwitz, J.,* 1995: Regional climate changes as simulated in time-slice experiments. *Climatic Change 31,* 273–304.

Davies, H.C., 1976: A lateral boundary formulation for multi-level prediction models. *Q. J. Roy. Meteor. Soc. 102,* 405–418.

Déqué, M., and *Piedelievre, J.P.,* 1995: High resolution climate simulation over Europe. *Clim. Dynam. 11,* 321–339.

Déqué, M., Rowell, D.P., Lüthi, D., Giorgi, F., Christensen, J.H., Rockel, B., Jacob, D., Kjellström, E., de Castro, M., and *van den Hurk, B.,* 2007: An intercomparison of regional climate simulations for Europe: assessing uncertainties in model projections. *Climatic Change (PRUDENCE Special Issue) 81,* 53–70.

Dümenil, L. and *Todini, E.,* 1992: A rainfall-runoff scheme for use in the Hamburg climate model. In *Advances in Theoretical Hydrology, A Tribute to James Dooge* (ed.: *J.P. O'Kane*). *European Geophysical Society Series on Hydrological Sciences 1.* Elsevier Press Amsterdam, 129–157.

Fouquart, Y. and *Bonnel, B.,* 1980: Computation of solar heating of the Earth's atmosphere: A new parameterization. *Beitr. Phys. Atmos. 53, 35–62.*

GARP, 1975: *The Physical Basis of Climate and Climate Modeling. Report of the International Study Conference in Stockholm, Global Atmospheric Research Program (GARP) 16.* World Meteorological Organization, Geneva, Switzerland, 265 pp.

Giorgi, F. and *Bates, G.,* 1989: The climatological skill of a regional model over complex terrain. *Mon. Weather Rev. 117,* 2325–2347.

Hagemann, S. and *Jacob, D.,* 2007: Gradient in the climate change signal of European discharge predicted by a multi-model ensemble. *Climatic Change (PRUDENCE Special Issue) 81, Supplement 1, 309–327.*

Hagemann, S., Machenhauer, B., Jones, R., Christensen, O.B., Déqué, M., Jacob, D., and *Vidale, P.L., 2004:* Evaluation of water and energy budgets in regional climate models applied over Europe. *Clim. Dynam. 23,* 547–567.

Jacob, D., Bärring, L., Christensen, O.B., Christensen, J.H., Hagemann, S., Hirschi, M., Kjellström, E., Lenderink, G., Rockel, B., Schär, C., Seneviratne, S.I., Somot, S., van Ulden, A., and *van den Hurk, B.*, 2007: An inter-comparison of regional climate models for Europe: Design of the experiments and model performance. *Climatic Change (PRUDENCE Special Issue) 81,* Supplement 1, 31–52.

Jacob, D. and *Podzun, R.,* 1997: Sensitivity studies with the regional climate model REMO. *Meteorol. Atmos. Phys. 63,* 119–129.

Lorenz, P. and *Jacob, D.,* 2008: Can two-way nesting improve a regional climate model simulation? *Geophys. Res. Abstracts 10,* 1607-7962/gra/EGU2008-A-11025, European Geosciences Union General Assembly 2008, Vienna, Austria.

Machenhauer, B., Windelband, M., Botzet, M., Christensen, J.H., Déqué, M., Jones, R.G., Ruti, P.M., and *Visconti, G.,* 1998: Validation and analysis of regional present-day climate and climate change simulations over Europe. *Report No. 275,* Max Planck Institute for Meteorology Hamburg, Germany.

Majewski, M., 1991: The Europa Modell of the Deutscher Wetterdienst. *ECMWF Seminar of Numerical Methods in Atmospheric Models II,* ECMWF, 147–191.

Marsland, S.J., Haak, H., Jungclaus, J.H., Latif, M., and *Röske, F.,* 2003: The Max Planck Institute global ocean/sea-ice model with orthogonal curvilinear coordinates. *Ocean Model. 5,* 91–127.

Mesinger, F. and *Arakawa, A.,* 1976: Numerical methods used in atmospheric models. *GARP Publications Series 17,* 1.

Mitchell, T.D., Carter, T.R., Jones, Ph.D., Hulme, M., and *New, M.,* 2004: A comprehensive set of climate scenarios for Europe and the globe. *Tyndall Centre Working Paper 55.*

Monin, A.S. and *Obukhov, A.M.,* 1954: Basic laws of turbulent mixing in the ground layer of the atmosphere. *Doklady Akademii Nauk SSSR Trudy Instituta Geofiziki 151,* 163–187.

Morcrette, J.-J., Smith, L., and *Fouquart, Y.,* 1986: Pressure and temperature dependence of the absorption in longwave radiation parameterizations. *Beitr. Phys. Atmos. 59,* 455–469.

Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grübler, A., Jung, T.Y., Kram, T., La Rovere, E.L., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H., Price, L., Raihi, K., Roehrl, A., Rogner, H.-H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S., Swart, R., van Rooijen, S., Victor, N., and *Dadi, Z.,* 2000: *IPCC Special Report on Emissions Scenarios.* Cambridge University Press, Cambridge.

Nordeng, T.E., 1994: Extended versions of the convective parametrization scheme at ECMWF and their impact on the mean and transient activity of the model in the tropics. ECMWF Research Department. *Technical Memorandum No. 206,* European Centre for Medium Range Weather Forecasts, Reading, UK.

Roeckner, E., Arpe, K., Bengtsson, L., Christoph, M., Claussen, M., Dümenil, L., Esch, M., Giorgetta, M., Schlese, U., and *Schulzweida, U.,* 1996: The atmospheric general circulation model ECHAM-4: Model description and simulation of present-day climate. *Report No. 18,* Max Planck Institute for Meteorology, Hamburg, Germany.

Roeckner, E., Bäuml, G., Bonaventura, L., Brokopf, R., Esch, M., Giorgetta, M., Hagemann, S., Kirchner, I., Kornblueh, L., Manzini, E., Rhodin, A., Schlese, U., Schulzweida, U., and *Tompkins, A.,* 2003: The atmospheric general circulation model ECHAM5. Part I: Model description. *Report No. 349,* Max Planck Institute for Meteorology, Hamburg, Germany.

Simmons, A.J. and *Burridge, D.M.,* 1981: An energy and angular-momentum conserving vertical finite-difference scheme and hybrid vertical coordinates. *Mon. Weather Rev. 109,* 758–766.

Simmons, A.J. and *Gibson, J.K.,* 2000: The ERA-40 Project Plan. *ERA-40 Project Report Series*, 1.

Sundquist, H., 1978: A parameterization scheme for non-convective condensation including prediction of cloud water content. *Q. J. Roy. Meteor. Soc. 104,* 677–690.

Szentimrey, T. and *Bihari, Z.*, 2007: Mathematical background of the spatialinterpolation methods and the software MISH (Meteorological Interpolationbased on Surface Homogenized Data Basis). Proceedings of the Conference on Spatial Interpolation in Climatology and Meteorology (eds.: *S. Szalai, Z. Bihari, T. Szentimrey* and *M. Lakatos*) 2007, COST Office, Luxemburg, ISBN 92-898-0033-X, pp.17-28.

Szépszó, G., 2008: Validation of the REMO regional climate model over the Carpathian Basin. *Poster, European Geosciences Union General Assembly 2008*, Vienna, Austria. http://clavier-eu.org/clavier/?q=system/files/szepszo-2008-EGUViennaPoster.pdf

Tiedtke, M., 1989: A comprehensive mass flux scheme for cumulus parameterization in large scale models. *Mon. Weather Rev. 117,* 1779–1800.

Warrilow, D.A., Sangster, A.B., and *Slingo, A.,* 1986: Modeling of land surface processes and their influence on European climate. *Technical Note DCTN 38,* Dynamical Climatology Branch, United Kingdom Meteorological Office.

Wilby, R.L., Wigley, T.M.L., Conway, D., Jones, P.D., Hewitson, B.C., Main, J., and *Wilks, D.S.,* 1998: Statistical downscaling of General Circulation Model Output: A Comparison of Methods. *Water Resour. Res. 34,* 2995–3008.