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REGIONAL CLIMATE MODEL VALIDATION FOR CENTRAL/EASTERN EUROPE USING HYDROSTATIC VS NON-HYDROSTATIC APPROACHES

Tímea Kalmár[1], Ildikó Pieczka[1], Rita Pongrácz[1,2*], Judit Bartholy[1,2]
[1]Dept. of Meteorology, Eötvös Loránd University, Budapest, Hungary
[2]Faculty of Science, Excellence Center, Eötvös Loránd University, Martonvásár, Hungary

1. INTRODUCTION

The regional climate is determined by the interactions of planetary processes and the large-to-local-scale processes. General circulation models (GCMs) still use horizontal resolution in the order of 100 km in century-long simulations, which do not allow them to fully represent local and regional topographic characteristics. Regional climate models (RCMs) are commonly used for dynamical downscaling, and increase the regional climate information consistent with the large-scale circulation supplied by the driving GCM or by reanalysis data at the boundaries of the RCM. RCMs are also widely used to provide projections on how the climate may change locally (Christensen et al. 2007). Therefore the evaluation of models against observations for different regions, and testing of the model sensitivity with respect to the parameterizations of the important physical processes (e.g. cloud formation and development, radiative processes) are necessary.

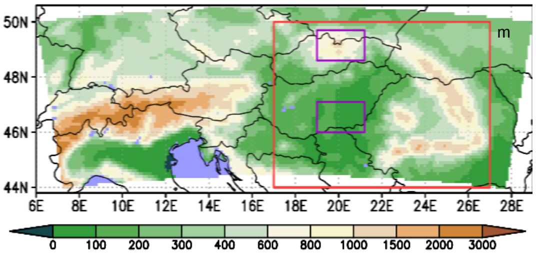

Fig. 1: The topography of the integration domain for the RegCM4.5 and RegCM4.6 simulations at 10 km horizontal resolution. Validation is shown for the eastern half of the RegCM integration domain covering the CARPATCLIM domain (indicated by red rectangle on the map). In addition, two special geographical subregions with different climatic conditions are selected for more detailed validation: the purple rectangles indicate the Tatra mountain (the northern subregion - highland) and the Great Hungarian Plain (the southern subregion - lowland).

The Department of Meteorology at the Eötvös Loránd University has gained an experience of using RegCM (Regional Climate Model; see e.g., Torma et al., 2008, 2011; Pieczka et al., 2016) for about a decade. The current study fits into the above series of analyses with evaluating the impact of different dynamical core (hydrostatic and non-hydrostatic) and microphysics parameterization schemes on model performance focusing on the Carpathian region – located in central/eastern Europe – at fine (10 km) horizontal resolution for a 10-year-long period (1981-1990). The experiments have been completed using the Regional Climate Model versions 4.5 and 4.6 (RegCM4.5 and RegCM4.6; available from the ICTP, Trieste). The new versions of RegCM include two main improvements: (i) the possible use of a non-hydrostatic dynamical core; and (ii) a new microphysics scheme was added. 10 km resolution was chosen to allow both hydrostatic and non-hydrostatic approaches in the simulations. Our main goal is to reconstruct the historical regional precipitation characteristics of the Carpathian region as reliable as possible. In this detailed validation study RegCM outputs are compared to the homogenized, 0.1° resolution CARPATCLIM data as reference, since the gridded time series are based on the measurements of regular meteorological stations within the Carpathian region (Fig. 1).

2. REGIONAL CLIMATE MODEL REGCM

Regional climate model RegCM originally stems from the National Center for Atmospheric Research/ Pennsylvania State University (NCAR/PSU) Mesoscale Model version MM4 (Dickinson et al., 1989; Giorgi, 1989), now maintained at the International Centre for Theoretical Physics (ICTP). RegCM4.5 (and RegCM4.6) is based on the dynamics of NCAR mesoscale model version 5 (MM5; Grell et al., 1994). One of the main improvements in this version is that the model can use a non-hydrostatic dynamical core, which allows for the small horizontal resolutions of the order of a few kilometers. The full description of model equations and possible parameterizations available in the version 4.5 (and 4.6) can be found in Elguindi et al. (2014) in detail. The hydrostatic and non-hydrostatic model dynamic equations and numerical discretizations are available in detail in Grell et al. (1994). We used the Biosphere-Atmosphere Transfer Scheme (BATS) to describe the role of vegetation and interactive soil moisture in modifying the surface-atmosphere exchanges of momentum, energy, and water vapor (Dickinson et al., 1993). The convective precipitation parameterizations used in this study are the Grell (1993) scheme over land and the MIT-Emanuel scheme (Emanuel, 1991; Emanuel and Zivkovic-Rothman, 1999) over sea. The turbulent transports of sensible heat, momentum and

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[*] *Corresponding author address:* Rita Pongracz, Dept. of Meteorology, Eötvös Loránd University, Pázmány st. 1/a. Budapest, H-1117; Hungary; e-mail: prita@nimbus.elte.hu

water vapor in the planetary boundary layer (PBL) over land and ocean are calculated using the scheme developed by Holtslag et al. (1990), which permits non-local transport in the convective boundary layer. Different resolved-scale cloud microphysics schemes are built in the model version 4.5 (and 4.6), e.g., the Subgrid Explicit Moisture Scheme (SUBEX, Pal et al., 2000) and new cloud microphysics scheme (NMIC, Nogherotto et al., 2016).

The RegCM4.6 does not contain major methodological modification; just some bugs have been fixed (Giorgi et al., 2016).

2.1 *The Subgrid Explicit Moisture Scheme (SUBEX)*

In the earlier RegCM versions, the resolved-scale cloud physics are treated by the SUBEX (Pal et al., 2000), which calculates fractional cloud cover as a function of grid point average relative humidity and includes only one prognostic equation for cloud water. Rain is calculated diagnostically from the cloud liquid and it forms when the in-cloud liquid water exceeds a temperature-dependent threshold (Sundqvist et al., 1989). In this scheme the ice and snow phases were not treated directly. SUBEX also includes the evaporation and accretion processes for stable precipitation.

2.2 *The new cloud microphysics scheme (NMIC)*

The new parameterization is based on a multi-phase one-moment cloud microphysics scheme built upon the implicit numerical framework recently developed and implemented in the ECMWF (European Centre for Medium-Range Weather Forecasts) operational forecasting model (Tiedtke, 1993; Tompkins, 2007). The parameterization solves five prognostic equations for water vapor, cloud liquid water, rain, cloud ice, and snow mixing ratios (Fig. 2). Compared to the pre-existing SUBEX scheme, it allows a proper treatment of mixed-phase clouds and a more realistic physical representation of cloud microphysics and precipitation. The new cloud microphysics parameterization scheme is described in detail in Nogherotto et al., 2016.

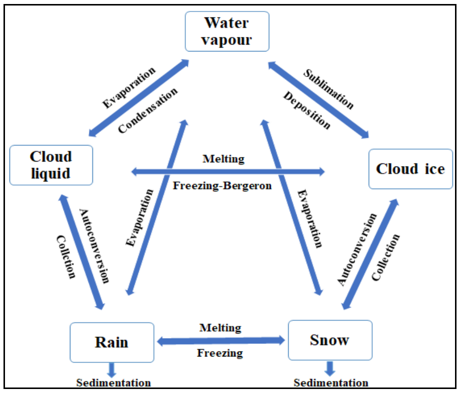
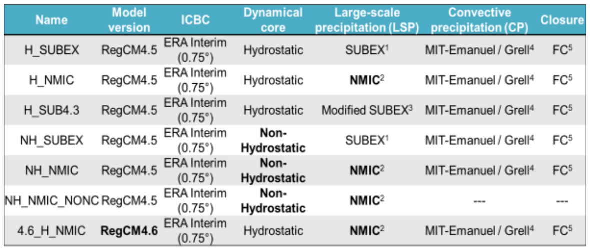


Fig. 2: New cloud microphysics scheme (Nogherotto et al., 2016)

3. DESCRIPTION OF MODEL EXPERIMENTS AND VALIDATION DATA

Simulations were carried out for the period 1981–1990 with initial and lateral boundary conditions (ICBCs) from the 0.75° horizontal resolution ERA-Interim data (Berrisford et al., 2011). In our simulations we used different large-scale parameterization schemes and dynamical cores. The main properties of the completed simulations are shown in Fig. 3. Our simulation matrix contains 7 different model simulations: the RegCM4.5 was run both in hydrostatic and non-hydrostatic mode with different large-scale precipitation schemes (SUBEX, modified SUBEX and NMIC). One simulation uses non-hydrostatic dynamics and NMIC, but the convective parameterizations are switched off and the deep convection is resolved explicitly. Furthermore, the newest RegCM4.6 was compared to RegCM4.5 in the case of the best performing model setup (hydrostatic and NMIC).

The main differences in the SUBEX parameterization between the H_SUBEX and H_SUB4.3 is that the cloud to rain autoconversion rate was decreased from 0.0005 to 0.00025 s^{-1}, the raindrop evaporation rate coefficient was increased from 0.2×10^{-4} to 1.0×10^{-3} (kg m^{-2} s^{-1})$^{-1/2}$ s^{-1}, and the raindrop accretion rate was decreased from 6 to 3 m^{3} kg^{-1} s^{-1} (Torma et al., 2008). The modified parameters have been built into the RegCM version 4.3 (Elguindi et. al, 2011), but they were changed back to the previous values in the RegCM4.5 and RegCM4.6 versions.



Name	Model version	ICBC	Dynamical core	Large-scale precipitation (LSP)	Convective precipitation (CP)	Closure
H_SUBEX	RegCM4.5	ERA Interim (0.75°)	Hydrostatic	SUBEX[1]	MIT-Emanuel / Grell[4]	FC[5]
H_NMIC	RegCM4.5	ERA Interim (0.75°)	Hydrostatic	**NMIC**[2]	MIT-Emanuel / Grell[4]	FC[5]
H_SUB4.3	RegCM4.5	ERA Interim (0.75°)	Hydrostatic	Modified SUBEX[3]	MIT-Emanuel / Grell[4]	FC[5]
NH_SUBEX	RegCM4.5	ERA Interim (0.75°)	**Non-Hydrostatic**	SUBEX[1]	MIT-Emanuel / Grell[4]	FC[5]
NH_NMIC	RegCM4.5	ERA Interim (0.75°)	**Non-Hydrostatic**	**NMIC**[2]	MIT-Emanuel / Grell[4]	FC[5]
NH_NMIC_NONC	RegCM4.5	ERA Interim (0.75°)	**Non-Hydrostatic**	**NMIC**[2]	---	---
4.6_H_NMIC	**RegCM4.6**	ERA Interim (0.75°)	Hydrostatic	**NMIC**[2]	MIT-Emanuel / Grell[4]	FC[5]

Fig. 3: Summary of the simulation details. 1: SUBEX (Pal et al., 2000); 2: NMIC: New cloud microphysics scheme (Nogherotto et al., 2016); 3: Modified SUBEX (Pal et al., 2000, Torma et al., 2011); 4: MIT-Emanuel (1991) over sea and Grell (1993) over land; 5: FC - Fritsch and Chappell (1980)

For the purpose of validation, we used the corresponding time period from the CARPATCLIM, which is a high resolution homogeneous gridded database for the Carpathian region with 0.1° horizontal resolution, covering the 1961–2010 period, containing all the major surface meteorological variables (Szalai et al., 2013; Spinoni et al., 2015). Daily temperature and precipitation datasets were downloaded, of which monthly, seasonal, and annual means were calculated for the validation domain (44–50°N, 17–27°E), and compared to the simulated values. In addition, two special geographical subregions with different climatic conditions were selected for more detailed validation

(Fig. 1): the purple rectangles indicate the Tatra Mountains (in the northern part of the domain) and the Great Hungarian Plain (in the southern part of the domain).

4. GENERAL RESULT – ENTIRE DOMAIN

4.1 *Precipitation*

For the seasonal mean precipitation biases, results for all the four seasons are shown in Fig. 4. Precipitation evidently depends on elevation, and similar dependence can be found in precipitation biases. This is the most pronounced in the warm months of the year, especially in summer: the largest negative biases compared to the CARPATCLIM are found over the northern-northeastern part of the Carpathian Mountains. Contrary to the other simulations, the 4.6_H_NMIC overestimates the precipitation significantly in all season over the whole domain. The overestimation is around 300% in summer in this simulation. The causes of the overestimation are not clear yet; it needs further test runs to clarify and detailed discussion with the RegCM developers (this is already in progress).

The results of NH_NMIC_NONC also substantially differ from the other simulations. The NH_NMIC_NONC produces the largest negative biases over lowlands: the biases are around -100%. It could be related to the fact that this simulation does not use convective parameterization over land and the 10 km horizontal resolution is not fine enough for the model dynamics to simulate appropriately the deep convection. However, this simulation overestimates the precipitation over the mountainous area as well as the majority of simulations.

The precipitation is overestimated with RegCM4.5 simulations in all seasons over the Carpathian Mountains by ~50%. Compared to the CARPATCLIM data the H_SUBEX and H_SUB4.3 result in the lowest mean precipitation bias (only 5% in summer and autumn) over the Great Hungarian Plain, except in spring when the largest bias reaches 30%.

Comparing the hydrostatic and non-hydrostatic dynamical cores, the latter produced more precipitation over the mountains and less over the lowlands. Moreover, seasonal mean precipitation bias values for Hungary substantially decreased with the NH_NMIC simulation.

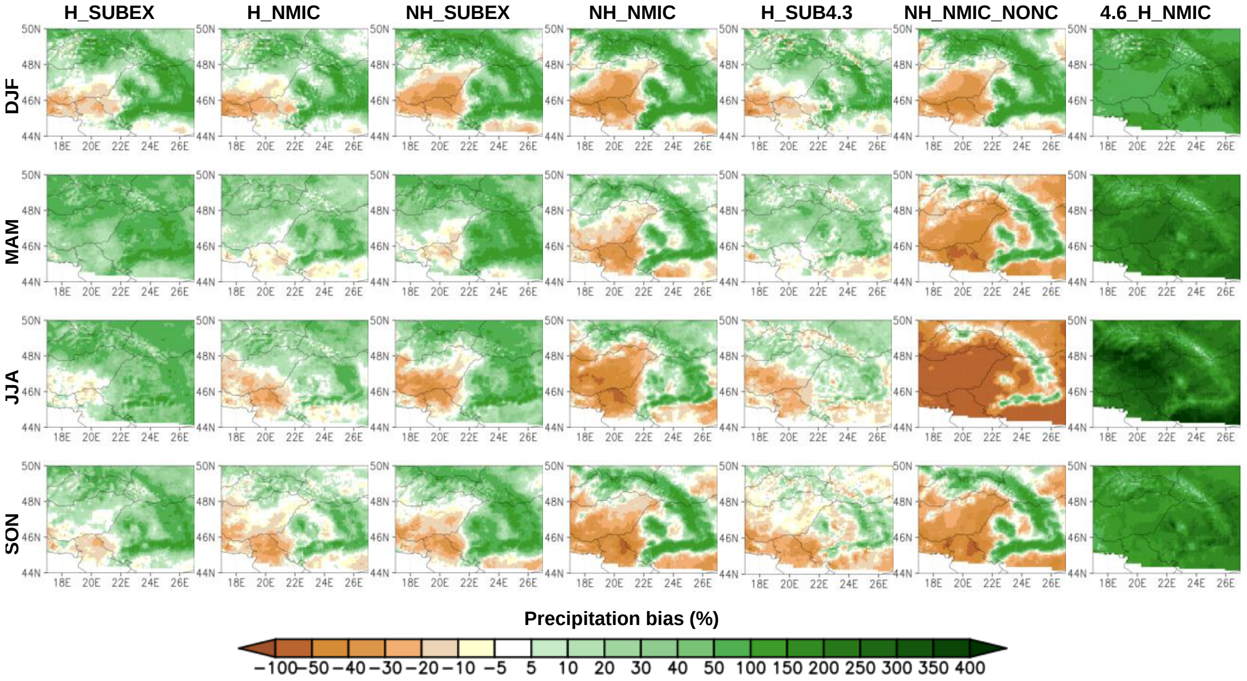


Fig. 4: The seasonal average precipitation bias of 10-km horizontal resolution RegCM4.5 and RegCM4.6 simulations, 1981–1990. (Validation data: CARPATCLIM)

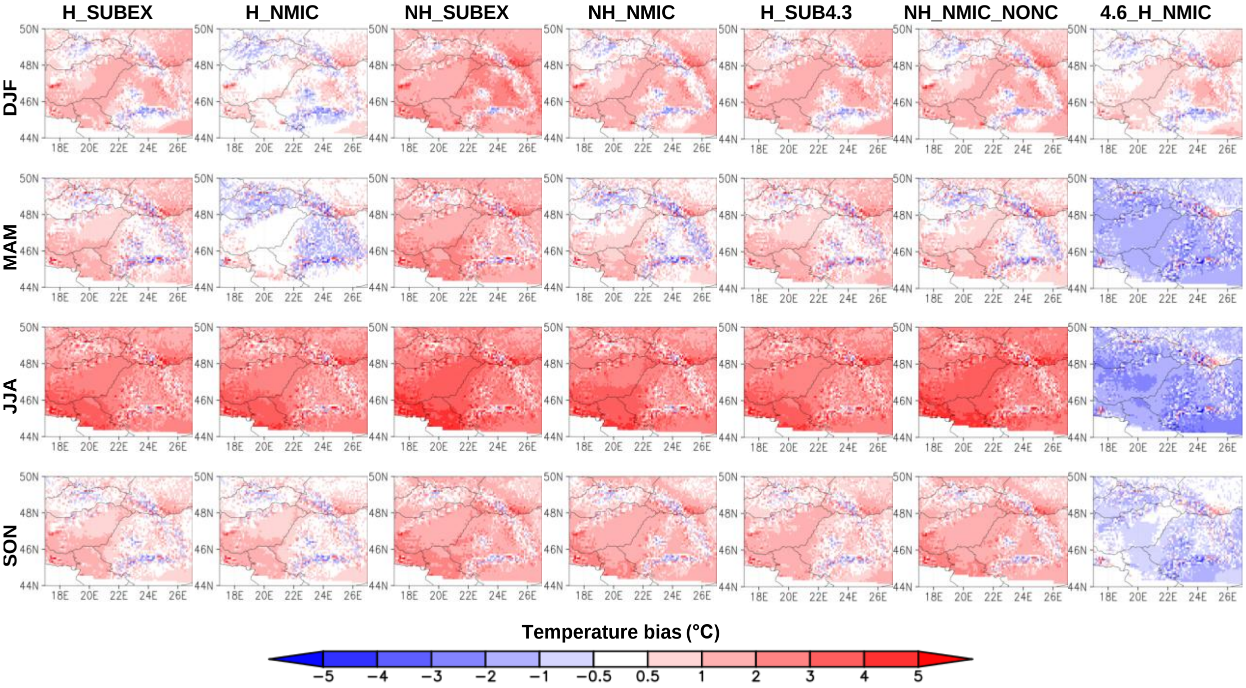


Fig. 5: The seasonal average temperature bias of 10-km horizontal resolution RegCM4.5 and RegCM4.6 simulations, 1981–1990. (Validation data: CARPATCLIM)

4.2 *Temperature*

In order to analyze the simulation results, the simulated temperature biases are mapped on seasonal scales for 1981–1990 (Fig. 5). The spatially averaged mean temperature bias for summer is around 3 °C (overestimation) for the entire CARPATCLIM domain with the RegCM4.5 simulations. As a major difference from this, the 4.6_H_NMIC shows underestimation (around –2 °C in summer). This negative bias could be related to the overestimation of precipitation, particularly the convective precipitation. The spatial distribution of temperature biases is similar in winter when the lack of convection can explain the results. The underestimation of RegCM4.6 also appears in spring and autumn when RegCM4.5 simulations mostly overestimate the observed temperature.

The signs of the seasonal mean errors in the mountainous areas change within short distances, especially when the error is close to zero. This can be connected to the fact that the observation network is not as dense in these areas as our grid resolution is, so the reference data might contain higher uncertainty.

The main differences between the RegCM4.5 runs can be found in winter and spring: the H_NMIC reproduces the average temperature better in Hungary (the bias is between –0.5 °C and 0.5 °C), but it underestimates in the Carpathians (the bias is greater than in Hungary, between –1 °C and –2 °C). In autumn and winter the Lake Balaton appears with a positive temperature bias in all RegCM4.5 simulations, which can be explained by the surface cover, namely, the developers changed the interpolation algorithm (RegCM4.3 used bicubic previously, whereas RegCM4.5 uses bilinear interpolation). Thus, the Lake Balaton appears as a water surface in RegCM4.5 where the model uses different parameterization scheme (i.e.g cumulus convection parameterization) from the schemes over the land surfaces.

The NH_SUBEX simulation produces the greatest positive biases: the differences between this simulation and CARPATCLIM are between –1 °C and +5 °C. The spatial distributions of the bias fields show that the minimum values occur over the mountainous areas of the domain.

Furthermore, the seasonal temperature biases between H_NMIC and NH_NMIC are quite small despite the precipitation differences in Fig. 4.

5. SPECIFIC RESULTS – SELECTED SUBREGIONS

In addition, we selected two special geographical subregions with different climatic conditions for more detailed validation: the Tatra Mountain and the Great Hungarian Plain. Here, we summarize the results for these selected regions.

5.1 *Temperature and precipitation*

The time series of monthly mean temperature bias are shown in Fig. 6 for 10 years for both subregions. A clear annual cycle can generally be recognized since the biases are smaller in winter than in summer. In general, the biases are smaller over the mountainous area compared to the lowland.

The greatest differences between the simulations can be recognized in the summer temperature biases over the lowland, namely, the 4.6_H_NMIC produces negative biases, while the RegCM4.5 simulations overestimate the temperature. The differences between the RegCM4.5 and RegCM4.6 simulations in summer are around 5 °C. The NH_NMIC_NONC simulation mostly overestimates the temperature because of the lack of the precipitation.

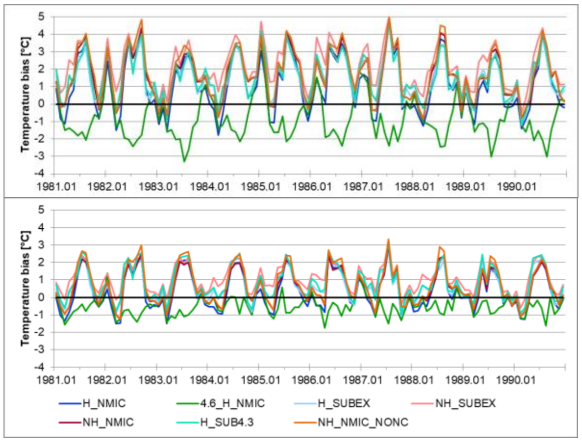


Fig. 6: Monthly mean temperature bias (°C) over the selected subregions (top: lowland – Hungarian Great Plains, bottom: mountainous area – Tatra). Reference: CARPATCLIM, 1981-1990.

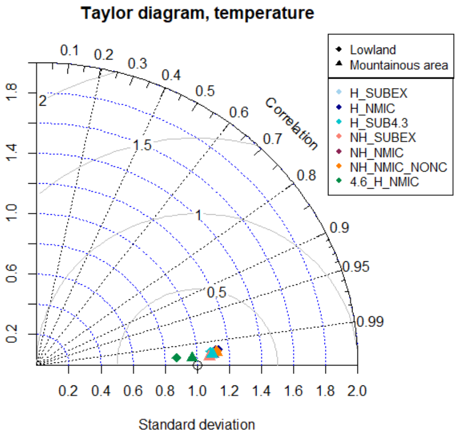


Fig. 7: Taylor diagram of the mean annual cycle of temperature simulated by the 7 simulations (Reference data: CARPATCLIM), 1981-1990.

The spatial averages of monthly mean temperature values were calculated for the two subregions and the CARPATCLIM domain for the 12 months of the year, which were then used to construct the Taylor diagram (Taylor, 2001). On the basis of Fig. 7, it can be concluded that only slight differences can be found between the individual experiments in temperature from a statistical point of view (i.e., RMSE values are small; standard deviation values with RegCM4.5 simulations are only a bit above the CARPATCLIM data; correlation coefficients are larger than 0.99). The statistical properties for temperature outputs are quite similar for the different model runs, as well as for the two selected subregions.

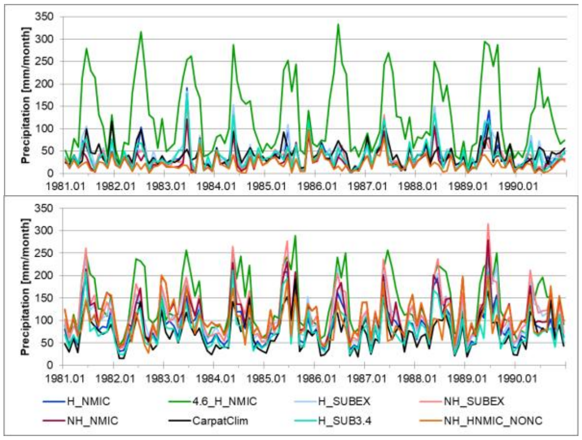


Fig. 8: Monthly simulated precipitation totals over the selected subregions (top: lowland – Hungarian Great Plains, bottom: mountainous area – Tatra) compared to the CARPATCLIM reference data (indicated by black line), 1981-1990.

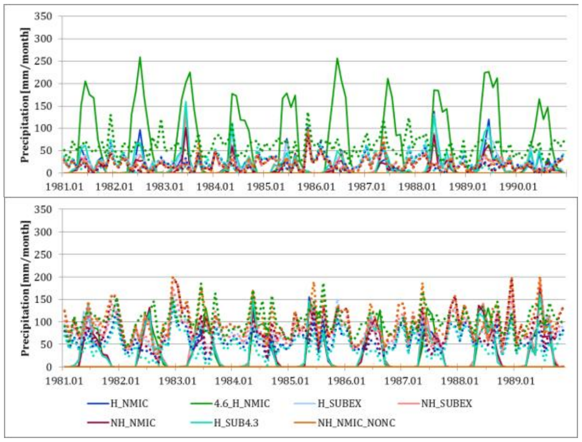


Fig. 9: Monthly simulated convective (solid line) and large-scale (dotted line) precipitation over the selected subregions (top: lowland – Hungarian Great Plains, bottom: mountainous area – Tatra), 1981-1990.

The simulated monthly precipitation totals over the selected subregions are shown in the Fig. 8 for 10 years. The black line represents the reference data (CARPATCLIM). The greatest values occur in the case of the RegCM4.6 simulation. 4.6_H_NMIC produces twofold precipitation in summer over the lowland compared to the other simulations. There are no significant differences between the simulations over the mountains, they all overestimate the reference data.

Fig. 9 compares the monthly simulated convective and large-scale precipitation over the selected subregions for 10 years. The outputs of simulations contain total precipitation and convective precipitation variables. The large-scale precipitation was calculated as the difference between the total and convective precipitation. Since the NH_NMIC_NONC does not use convective parameterization, convective precipitation is not calculated separately.

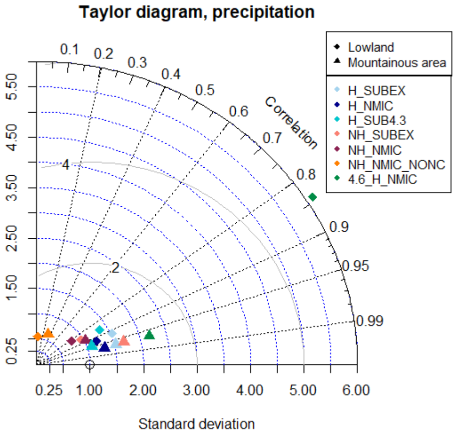


Fig. 10: Taylor diagram of the mean annual cycle of precipitation totals (mm/month) simulated by the 7 simulations (Reference data: CARPATCLIM), 1981-1990.

The statistical properties of precipitation (Fig. 10) show that the least succesful simulation is the 4.6_H_NMIC over the lowland: this simulation has the greatest standard deviation (>6 mm). The simulations with new microphysics are close to each other for both regions, except the NH_NMIC_NONC (and 4.6_H_NMIC). Moreover, the NH_NMIC_NONC underestimates the precipitation and the resulting correlation coefficient is the lowest.

5.2 *Comparison of H_NMIC and 4.6_HNMIC*

We could see that the results with version 4.6 are quite different from the results of the version 4.5. Therefore, we analyzed other variables that are strongly related with precipitation, namely, the soil moisture and evapotranspiration.

An accurate estimation of soil moisture plays a critical role in water balance calculation by hydrological and land-surface models as well as the GCMs (Robock et al., 2000). Soil moisture can influence weather through its impact on evaporation and other surface energy fluxes. The reliability of estimations is largely dependent upon model formulation, assumptions related to model parameterization, the quality of input data, and characterization of land surface heterogeneity (Mahmood, 1996).

Evapotranspiration is the link between the global water cycle, energy cycle, and carbon cycle; hence it is of critical importance for hydrology, ecology, and the entire climate system (Wang and Dickinson, 2012; Huang et al., 2014). Changes in evapotranspiration will also change the energy partitioning between sensible and latent heat, altering atmospheric dynamics and influencing weather and climate (Trenberth et al., 2009).

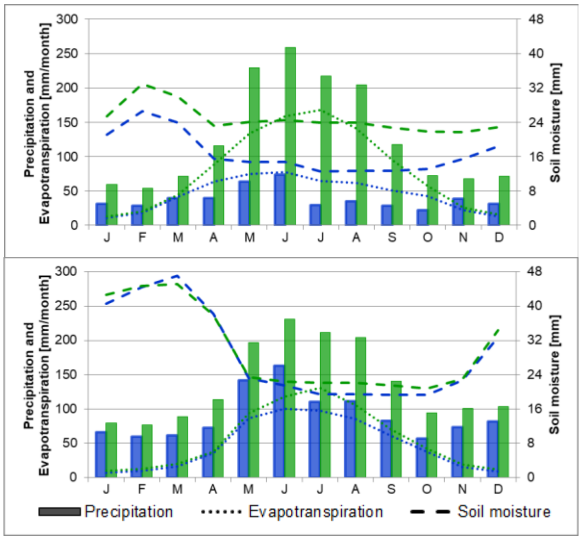


Fig. 11: Comparison of H_NMIC (blue) and 4.6_H_NMIC (green). Annual distribution of monthly mean simulated precipitation totals, evapotranspiration and soil moisture over the selected subregions (top: lowland – Hungarian Great Plains, bottom: mountainous area – Tatra), 1981-1990.

Fig. 11 shows the annual distribution of precipitation, evapotranspiration and soil moisture (we analyzed the upper 10 cm soil layer). The differences between RegCM4.5 and RegCM4.6 are greater over the lowland than over the mountainous are. The largest differences appear in late spring and summer in the annual distribution of monthly mean simulated precipitation totals. The main differences can be observed over the lowland. The simulated soil moisture show that the highest values appear in late winter/early spring. If the precipitation totals are high, then the values of soil moisture increase, which is caused by the snow melting.

The evapotranspiration shows a clear annual cycle, which depends on the temperature. The difference between the H_NMIC and 4.6_H_NMIC is greatest over the lowland in summer.

6. CONCLUSIONS

We analyzed the high-resolution (10-km grid spacing) simulation experiments of the RegCM4.5 and RegCM4.6 for the decade-long period 1981–1990 over the Carpathian basin. Our simulation matrix consists of hydrostatic and non-hydrostatic runs together with the different treatments of moisture (the SUBEX and the NMIC). On the basis of the results we can conclude that the RegCM4.6 produces substantially wetter and cooler climatic conditions than RegCM4.5, despite that the User’s Guide does not mention any major modification in the program code except computational debugging. The largest differences between simulated and observed temperatures occur in summer. Comparing the simulations, the H_NMIC seems to be the most promising over Hungary although it underestimates temperature in the Carpathian Mountains. The largest positive precipitation biases are found over the Carpathian Mountains in all seasons. Negative precipitation biases appear over the lower elevated regions.

More comprehensive sets of experiments are obviously needed in order to test the microphysics schemes in different model settings, especially towards its use in very high resolution, convection permitting simulations.

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