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Comparison of simulated and objectively analyzed distribution patterns of snow water equivalent over the Carpathian Region

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Abstract—Snow is a very important component of the climate system which controls surface energy and water balances. Its high albedo, low thermal conductivity, and properties of surface water storage impact regional to global climate. The various properties characterizing snow are highly variable and thus have to be determined as dynamically active components of climate. However, on large spatial scales, the properties of snow are not easily quantified either from numerical modeling or observations. Thus, it is vital to estimate the model performance in comparison with consistent datasets of assimilated data. Snow water equivalent data simulated with four different model configurations of the RegCM climate model over Central Europe for a time window of 10 consecutive winters are compared with the objective analysis data from the high-resolution CARPATCLIM database on monthly and seasonal basis. The CARPATCLIM snow water equivalent data are also modeled, but based on the gridded daily observation of the temperature, precipitation, and relative humidity. The results reveal good commensurability over the bigger, mostly flat part of the domain, however, they show significant discrepancies, mainly overestimation, over the Carpathian Region.

Key-words*: snow water equivalent, numerical simulation, RegCM*

1. Introduction

Snow is a very important component of the climate system which controls surface energy and water balances, and it is the largest transient feature of the land surface according *Yang et al.* (2001). It has an effect on atmospheric circulation through changes to the surface albedo, thermal conductivity, heat capacity, and aerodynamic roughness, as it has been documented in numerous observational and modeling studies (e.g., *Barnet et al.* 1989, *Gong et al.* 2003). The snow properties of the surface water storage control the availability of water in many ecosystems and to a sixth of the world's population (*Clifford,* 2010). Therefore, it is vital that snow is properly represented in geophysical models if we want to understand and make predictions of weather, climate, carbon cycle, flooding, and drought.

The various properties characterizing snow are highly variable and thus have to be determined as dynamically active components of climate. These include the snow depth (h_s) snow water equivalent (*SWE*), density, and snow cover area (*SCA*). To understand global snow water trends in the necessary depth, the most fundamental metric to assess is *SWE*, with h_s as a close second. However, on large spatial scales, the properties of snow are not easily quantified either from modeling or observations. For example, station based snow measurements often lack spatial representativeness, especially in regions, where the topography, vegetation, and overlaying atmosphere produce considerable heterogeneity of the snow-pack distribution (*Liston,* 2004). Thus, despite the weaknesses of the land surface models, the quantitative assessment of the snow properties by the means of the numerical simulation is a pragmatic approach for obtaining of the spatial and temporal continuous distribution of the snow pack. The utilization of regional climate models (RCMs) in the Bulgarian National Institute of Meteorology and Hydrology is within the framework of the common effort for composition of detailed picture of the snow cover and its dynamics over Southeast Europa with focal point to the central part of the Balkan peninsula. So, the latest version of the well-known RegCM regional climate model is applied for quantitative estimation of many surface variables, including *SWE*, for 14 consecutive winters between 2000 and 2013, and the subset 2000–2009 is used in the present study. As in many validation studies, however here even in greater extent, part of the difficulties in exploring the simulation ability issue of the model is rooted in the lack of validation data for small-scale features and reliable measurements. It is clear that datasets as the mentioned model simulation with such time gaps are highly insufficient for any model validation study. Nevertheless, hence such procedure is often treated in similar numerical experiments as a necessary (first) step in verification/model performance evaluation, such comparisons are preformed and the results are described (*Chervenkov et al.,* 2015). Main conclusion from this work is that the comparisons of the measurements with the model output from all runs yield generally similar results. Further, the overall (i.e., over the whole time span) biases are acceptable, but, however, with large discrepancies in the day-by-day comparisons, which is typical for climate modeling studies.

Satellite earth snow observation products have the needed spatial and temporal consistency, which allows comparisons with model output over continuous area and time frames. So, utilizing satellite data is a significant step ahead in the quantitative snow cover assessment. Satellite retrieval estimates, however, require inversion algorithms to relate raw signals recorded at the satellite to physical properties of the land surface, and these inverted estimates can contain errors and biases (*Hancock et al.,* 2013). Although among the other products, *SWE* has been proven to be more problematic (*Hancock et al.,* 2013), especially for wet snow and during melt, which is a typical case in southeast Europe, the common treatment of satellite data and model results has been already performed. The gridded digital maps of the Globsnow SWE product (http://www.globsnow.info/swe/GlobSnow_SWE_product_readme_v1.0a.pdf) are compared with the simulation output for the whole 14-year period on monthly basis (*Chervenkov et al.,* 2016). Certain drawbacks of the Globsnow product can point the absence of data for mountainous regions, which, at least from hydrological point of view, are important.

Another informational sources, suitable for assessment studies are the products of objective analysis of measurements. Depending on the leading physical and mathematical concept, involved data streams and, correspondingly, the incorporated processing methods the can vary greatly. The primary importance feature of these products is the data quality and, second, at least from the end-user point of view, the form of the final product, which is a timely continuous digital map of gridded datasets. The relatively long (in climatological sense, i.e., in order of decades) temporary extend, acceptable horizontal resolution, presence of subsets for various variables, and, not at least, the free-of-charge availability of most of these products make it a preferable tool in many applications, as the presented verification study here. Being typical member of this group, the CARPATCLIM dataset is a motivated choice for testing the model performance, and thus this paper, which, in some extend, is the continuation of *Chervenkov et al.* (2015), is dedicated to the comparison of the simulated values of *SWE* with the analyzed ones.

The paper is organized as follows: Short description of the CARPATCLIM database, the used version of the RCM RegCM, and the methodological approach are placed in the first chapter. The performed calculations and the obtained results are described and visualized in the second chapter. Summarizing remarks and the main conclusions are listed in the last chapter.

2. Concept and methodology

The CARPATCLIM database is the result of the common effort of 10 national institutions from 9 Central European countries as well as the Joint Research Centre and the Institute for Environment and Sustainability to overcome the differences caused by the national specification in the meteorological data sampling and management. According to the product description, the main aim of the project is to improve the basis of climate data in the Carpathian Region for applied regional climatological studies such as a Climate Atlas and/or drought monitoring, to investigate the fine temporal and spatial structure of the climate in the Carpathian Mountains and the Carpathian Basin with unified methods. Manifestation of the success of the project is the freely available, high resolution gridded database for the Larger Carpathian Region (LCR) (see *JRC report* 2010 and the references therein). For ensuring the usage of the largest possible station density, the processing were implemented by the countries themselves using the same methods and software. The commonly used methods were the MASH (Multiple Analysis of Series for Homogenization; *Szentimrey,* 2011) procedure for homogenization, quality control, and completion of the observed daily data series; and the MISH (Meteorological Interpolation based on Surface Homogenized Data Basis; *Szentimrey* and *Bihari,* 2007) for gridding of homogenized daily data series. The harmonization of the datasets was carried out by the exchange of the near border station data of the neighboring countries before and after homogenization.

The evaluation of measured snow cover records at the level of CARPATCLIM area has led to the conclusion that there is a lack of reliable and continuous measured data at the level of the meteorological stations of the region, and it is insufficient for estimating connected variables such as *SWE* and snow depth. This is a chronic problem in many regions of the world, in particular in the Balkan peninsula adjacent to the larger Carpathian Region, as shown in *Chervenkov et al.* (2015). In order to address this gap, a snow cover model employed operationally at the Austrian Central Institute for Meteorology and Geodynamics (ZAMG) was applied to generate a 0.1° latitude/longitude grid of daily mean snow cover and corresponding estimated water equivalent and snow depth simulations. The applied model is based on pre-finished CARPATCLIM grids of mean air temperature, precipitation sum, and relative air humidity. They are processed by the snow cover model regarding three main parts: accumulation of snow cover, ablation of snow cover, and transformation of *SWE* to snow depth. The reader can find more detailed description at http://www.carpatclim-eu.org/docs/computation/SNOW.pdf. The database contains the gridded distributions of 16 variables with horizontal resolution 0.1°×0.1° for domain with longitudinal extent 17 to 27 degrees north and latitudinal extent 44 to 50 degrees east for the period 1961–2010 on diurnal and monthly basis.

RCMs have been developed and extensively applied in the recent decade for dynamically downscaling of the coarse resolution information from different sources, such as global circulation models (GCMs) and reanalysis, for different purposes including past climate simulations and future climate projections. This widely used and productive approach is applied here. The main simulation tool is the freely available latest version of the regional climate model of the International Center of Theoretical Physics in Italy (ICTP). RegCM4 is a 3-dimensional, sigma-coordinate, primitive equation RCM with dynamical core based (version 2 and later) on the hydrostatic version of the NCAR-PSU Mesoscale Model 5 (MM5) (*Grell et al.,* 1994). The radiative transfer package is taken from the Community Climate Model version 3 (CCM3) (*Kiehl et al.,* 1996). The large-scale cloud and precipitation computations are performed by the Subgrid Explicit Moisture Scheme (SUBEX, *Pal et al.,* 2000), and the land surface physics are performed according to the Biosphere-Atmosphere Transfer Scheme (BATS, *Dickinson et al.,* 1993). The adopted convective scheme for the RCM simulations in the present study is the Grell scheme (*Grell,* 1993)) with the Arakawa and Schubert (*Arakawa* and *Schubert,* 1974) closure assumption. Main manifestation of the flexibility of the modern RCMs, including RegCM4, is the possibility for selection among different initial and boundary conditions datasets (ICBC), parameterization schemes/modules within the model, various constants and closure assumptions, etc., combining them in practically countless model setups. Obviously, the simulation output from such model setups will differ from one another, and, more or less, from the "reality". Thus, multiple runs with different model setups/configurations (further: modcons) have to be performed accenting the inspection of the modules that have major role is the proper description of the considered variables. There is overall agreement in the scientific community that the ICBC plays the most important role in the model performance (see *Xue et al.,* 2014 for details). Although there are numerous tests with different reanalysis data, which are considered as better ICBC compared to those produced by GCMs, there is no single reanalysis data set yielding the best results in every region and/or every season. We have performed simulations with the two most popular and widely used reanalysis datasets: the ERA-Interim of the European Centre for Medium-Range Weather Forecasts (ECMWF) (*Dee et al.,* 2011) with horizontal resolution 1.5°×1.5° for RegCM simulations, noted further as EIN15 and the reanalysis 2 of the USA National Centers for Environmental Predictions and the National Center for Atmospheric Research (NCEP/NCAR) (*Kanamitsu et al.,* 2002) with horizontal resolution 2.5°×2.5°, noted further as NNRP2. It is physically reasonable also to expect, that the module, which describes the surface processes and the interactions with the under- and overlaying soil and atmospheric layers, namely the land surface model, plays relevant role especially in the numerical treatment of the snow cover. A major addition to RegCM4 is the option to use the Community Land Model (CLM), version 3.5. Compared to BATS, CLM is a more advanced package (and, as a result, it is computationally heavier), which is described in detail in *Oleson et al.,* (2004, 2008). It uses a series of biogeophysically based parameterizations to describe the land-atmosphere exchanges of energy, momentum, water, and carbon. So, combining the two ICBC datasets with the two land surface models, four modcons are designed: ERAIN/BATS, ERAIN/CLM, NNRP2/BATS, and NNRP2/CLM, noted further as EB, EC, NB, NC.

The model domain is centered over Bulgaria and consists of 72×77 20 km×20 km gridcells and covers the CARPATCLIM one without the most northern latitudinal band in width 1.4° only. The simulation period is from November 1 till March 31 for 14 consecutive years between 2000 and 2014. The row model output is the gridded distribution of the *SWE* on a 6-hourly basis (i.e., at 00, 06, 12, and 18 UTC).

Traditional method to judge the model performance is to assess the degree of agreement between the model output and the analyzed data using well elaborated statistical methods, among them the most frequently applied is the calculation of statistical scores, which is widely used in validation studies.

3. Performed calculations and obtained results

Due to the practical absence of horizontal mixture processes, specific feature of the snow cover is the relatively high heterogeneity (in comparison to the atmospheric lower-level parameters). Thus, even on small distances in order of couple of kilometers, considerable differences in the snow properties can be observed, and the inspection of the CARPATCLIM *SWE* dataset confirms this peculiarity: the differences in some months and regions even for neighboring gridcells can be more than an order of magnitude. Hence, is reasonable to expect that the adequate resolution of the analysis and the model data, and the comparability of both of them is vital. As long as the resolution of the CARPATCLIM (roughly 10 km) is properly selected, the RegCM resolution of 20 km for the current implementation seems insufficient. Additionally, intending initially to obtain the mainly overall picture for a significantly larger domain, the subgridding option was not switched on in the model simulations, which is not applicable for the CLM option. Since interpolation procedures can not reveal smaller scale features than those presented in the original data, and generally all of these leads to smoothing of the field, is methodologically correct to interpolate the finer CARPATCLIM grid to the RegCM one and not vice versa. This is done in the most natural way, by simple spatial averaging of every neighboring 2×2 gridcells with definite values.

Although in some years and gridcells there is already snow cover before the 1st of November, the start of the model simulations at this date ensures generally the practical absence of significant snow pack over the bigger part of the domain. Starting relevantly later would cause systematic underestimations. Ten winters of the period 2000–2009 were taken in consideration in this study.

Usually January is treated as the representative month for the corresponding winter. The inspection of the CARPATCLIM atlas (available at http://www.carpatclim-eu.org/pages/atlas/), however, reveals that the snow cover over the bigger part of the domain for most of the considered years is thicker in February, and thus the average *SWE* for this month is the first considered climate characteristics. The second one is the monthly weighted average *SWE* for the winter, namely December, January, and February. Each month is weighted with the number of days per month.

Hence main aim of this work is to present the comparison between the simulated and analyzed *SWE*, rather than the actual *SWE* climatology, only an indicative sight is given here *Figs. 1* and *2*. It is worth to emphasize, however, its spatial and temporal variation – generally speaking, the *SWE* in the plains is roughly 10–50 mm, when over the Carpathian ridge it is up to 150–200 mm.

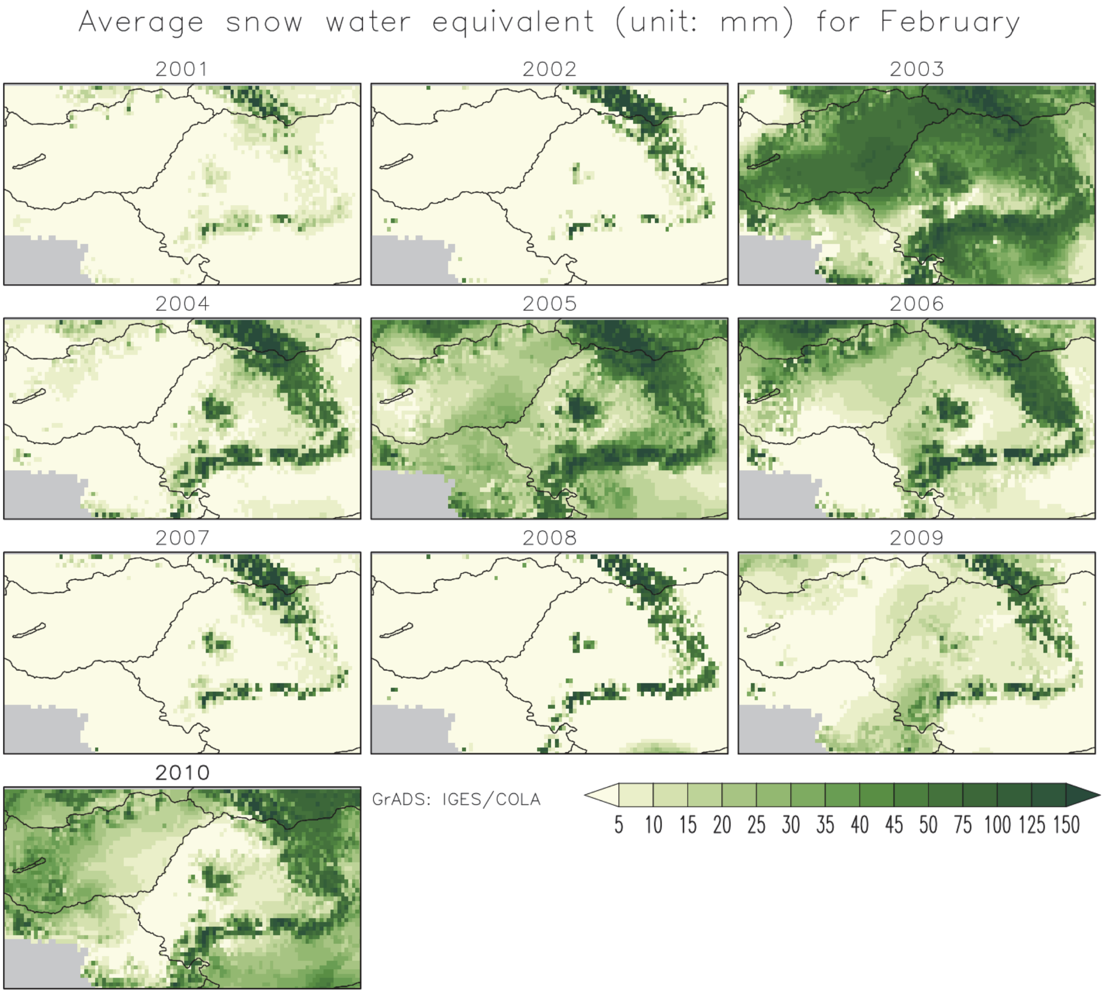

Fig. 1. Monthly average CARPATCLIM *SWE* (unit: mm) distribution for February in the original grid.

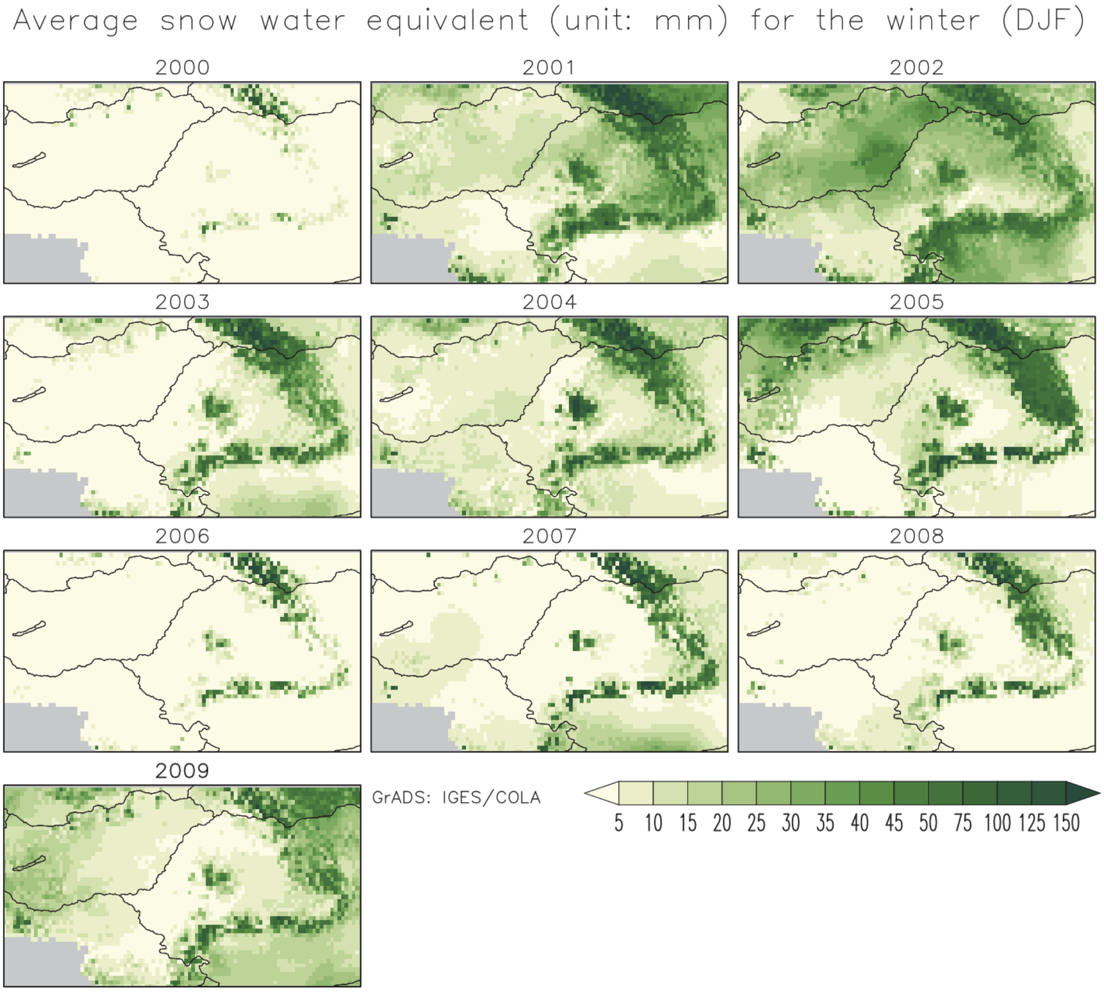

Fig. 2. Winter average (i.e., monthly weighted for December, January, and February) CARPATCLIM *SWE* (unit: mm) distribution in the original grid.

Keeping in mind the above described reasons about the resolution choice and intending to facilitate the comparisons, the modeled data are interpolated to the new, coarser CARPATCLIM 0.2°×0.2° grid. The files with the row RegCM output are handled with the powerful and easy-to-use operator suite climate data operator (*CDO,* 2015). The postprocessing of the model and analysis data is performed with purposely developed own programs, all tasks are automated via Linux bash scripts, and the visualization is done with GrADS scripts.

Most traditional approach for estimation of the departure of the model results from the analysis is applied: the absolute difference between the CARPATCLIM *SWE* and the modeled one (i.e., BIAS) for every winter month and for the monthly weighted winter average are calculated, but, due to the above commented relative importance, only those for February (in *Figs. 3–6*) and for the seasonal mean (in *Figs. 7–10*) are presented.

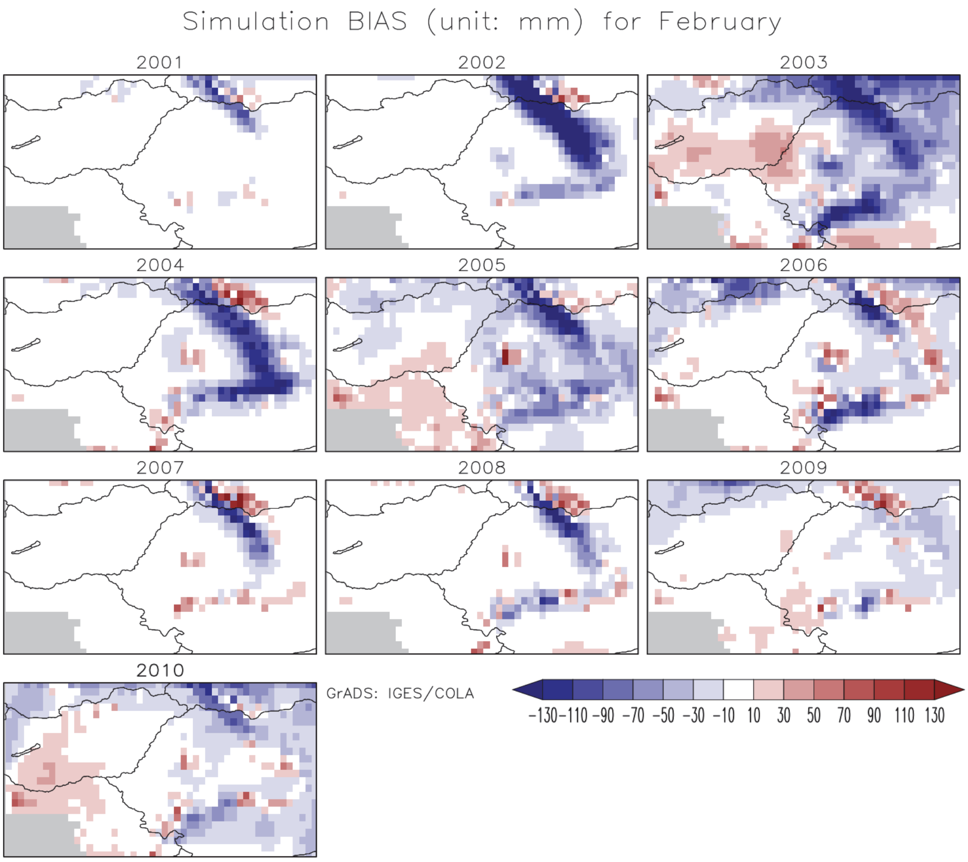

Fig. 3. BIAS (unit: mm) for the modcon 'EB' for February average in the reduced CARPATCLIM grid.

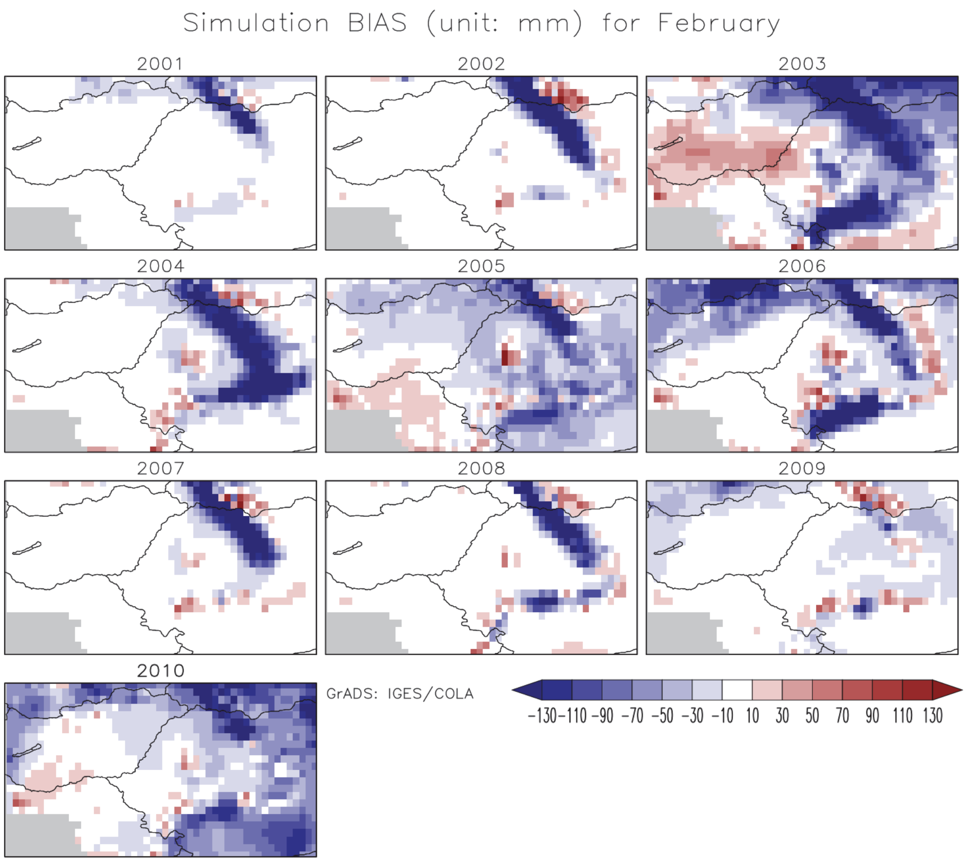

Fig. 4. Same as in *Fig. 3*, but for the modcon 'EC'.

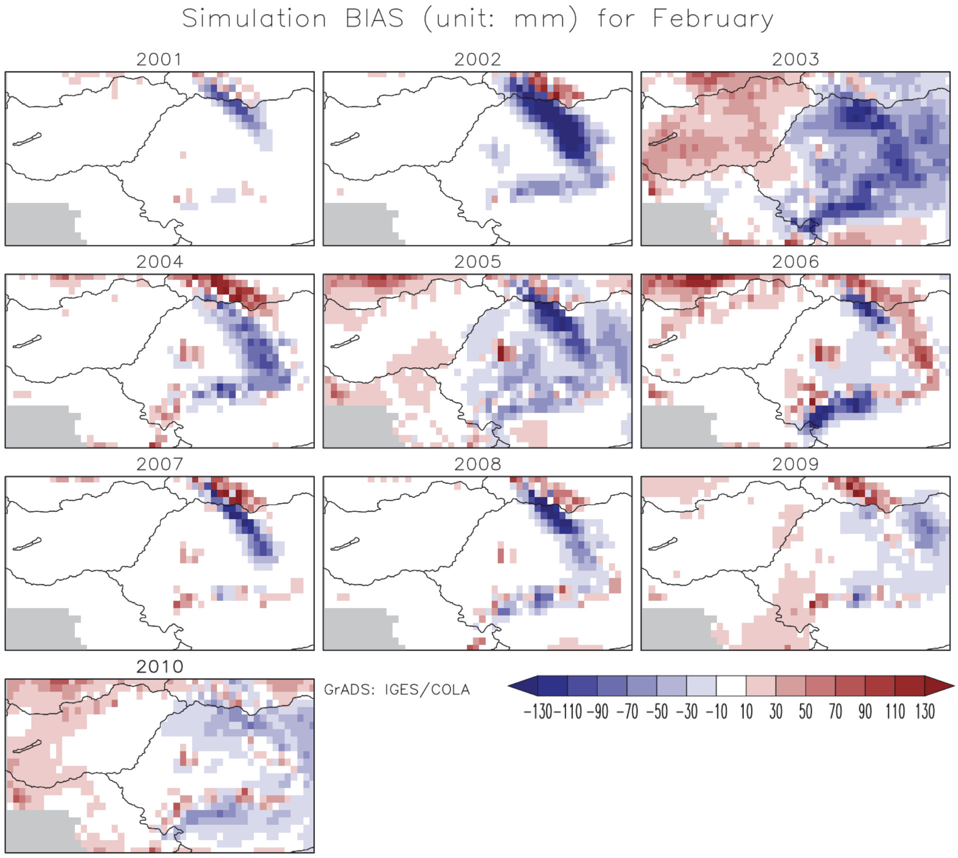

Fig. 5. Same as in *Fig. 3*, but for the modcon 'NB'.

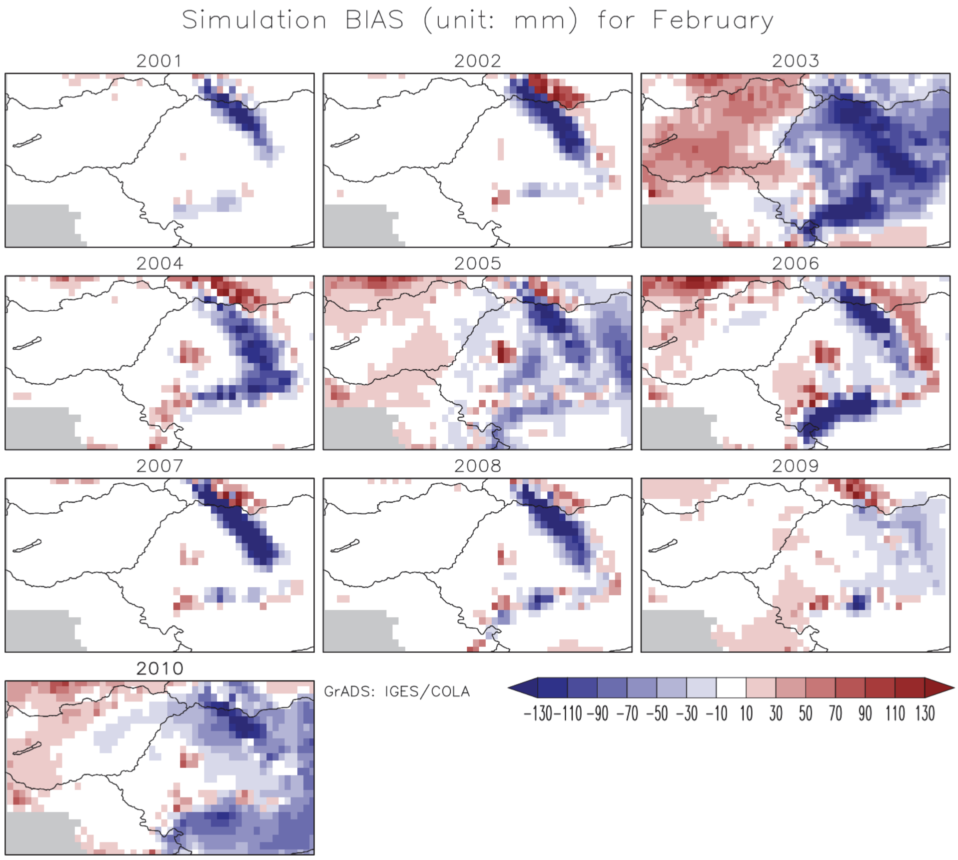

Fig. 6. Same as in *Fig. 3*, but for the modcon 'NC'.

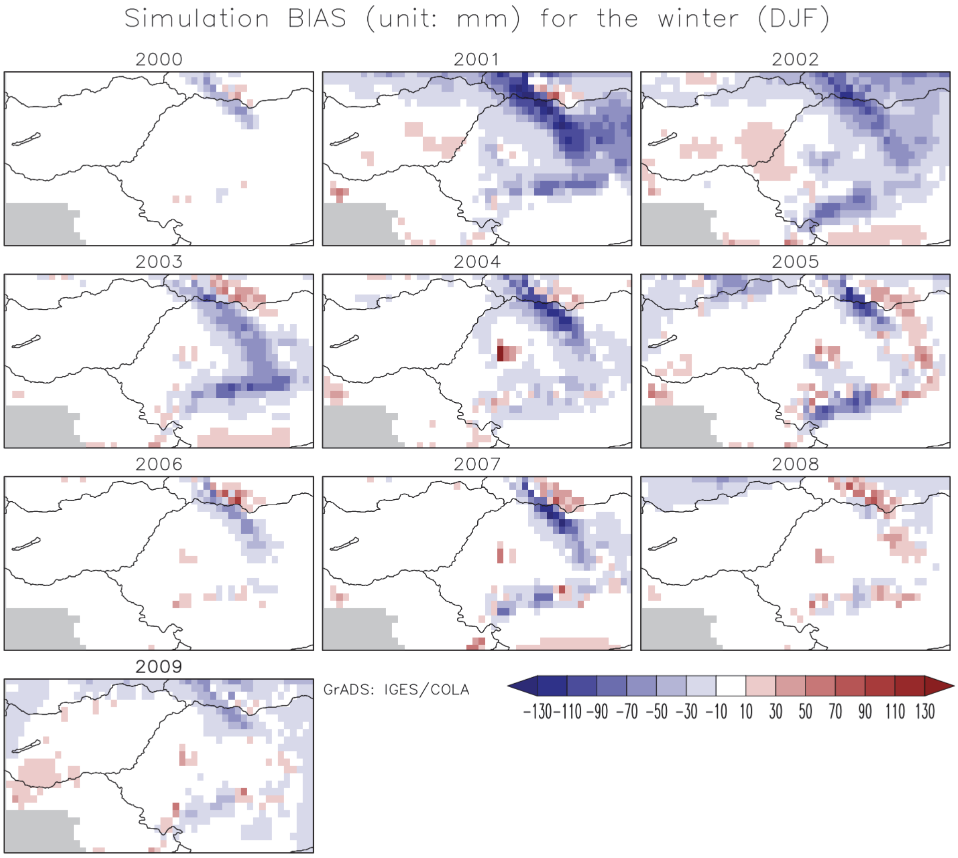

Fig. 7. BIAS (unit: mm) for the modcon 'EB' for the winter average in the reduced CARPATCLIM grid.

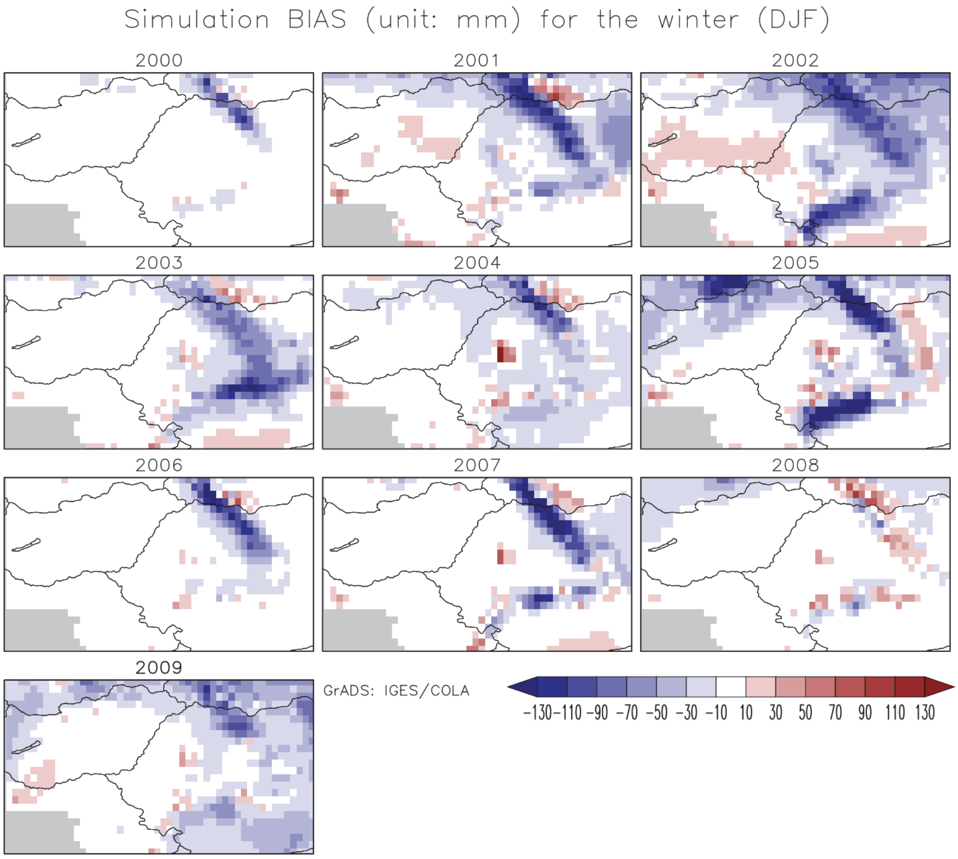

Fig. 8. Same as in *Fig. 7*, but for the modcon 'EC'.

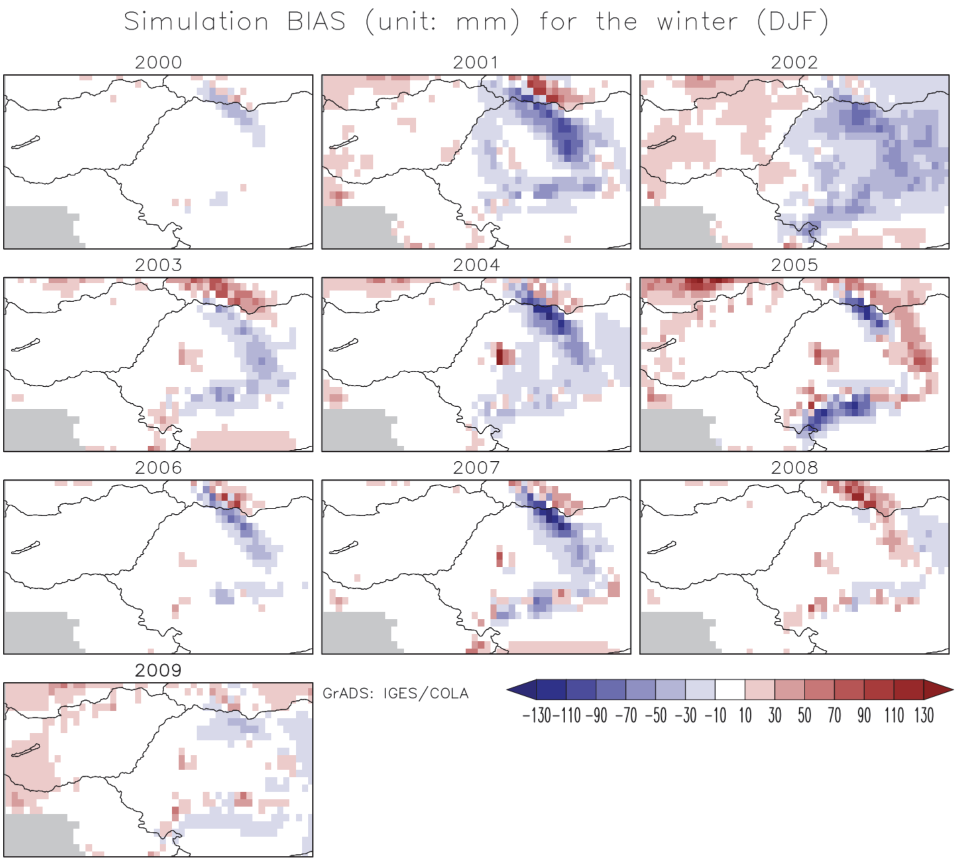

Fig. 9. Same as in *Fig. 7*, but for the modcon 'NB'.

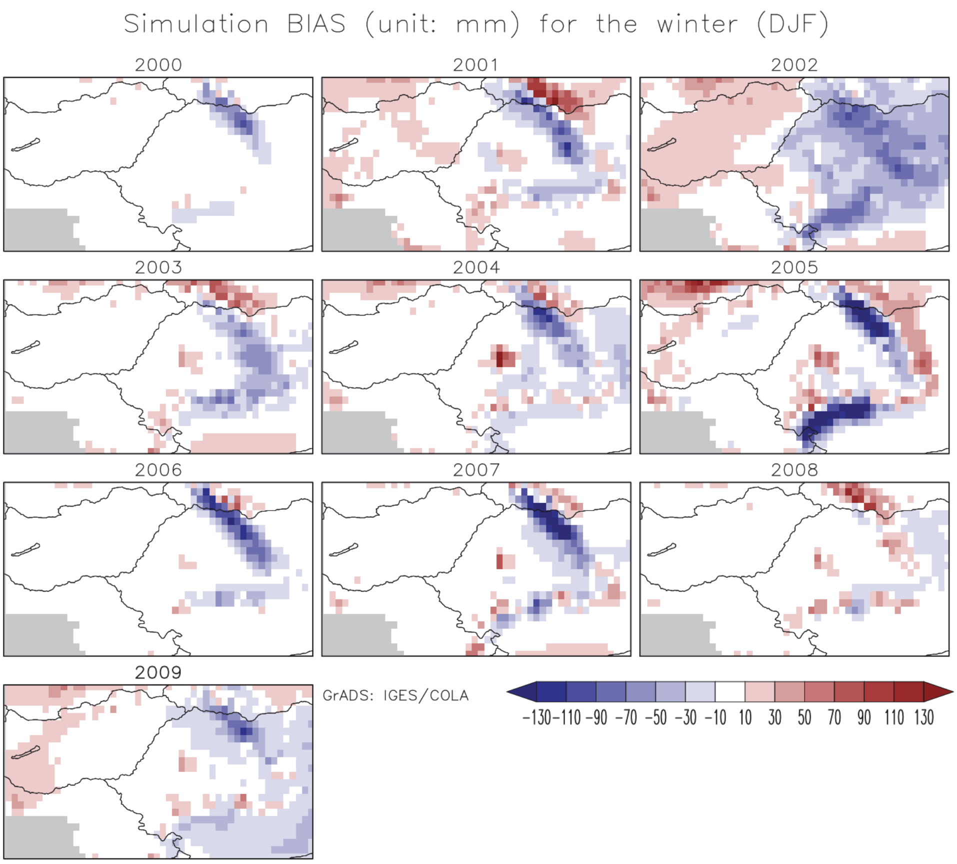

Fig. 10. Same as in *Fig. 7*, but for the modcon 'NC'.

The BIAS is formulated as:

$$BIAS = \frac{1}{N} \cdot \sum_{i=1}^{N} (O_i - M_i), \tag{1}$$

where O_i are the observed, in this case the CARPATCLIM values, M_i are the modeled ones and N is the number of pairs (comparisons).

Hence the spatial variability of the BIAS is significant, it is important to provide also the root mean square error (RMSE) averaged over the domain index, presented in *Table 1*. Using the notation of Eq. (1), the RMSE is equal to:

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (O_i - M_i)^2} . \tag{2}$$

This index can serve for the first (and rough) judgment of the spatially integrated criterion of the model performance. It is not latitudinal weighted, but, due to the relatively small extent of the domain along the meridian, this effect can be neglected.

Table 1. Values of the root mean square error (unit: mm)

Modcon	**EB**				**EC**				**NB**				**NC**			
Winter	**D**	**J**	**F**	**DJF**	**D**	**J**	**F**	**DJF**	**D**	**J**	**F**	**DJF**	**D**	**J**	**F**	**DJF**
2000	2.1	6.3	13.1	6.6	3.3	12.9	25.1	13.1	2.0	5.7	12.2	6.0	2.2	9.5	21.0	10.2
2001	30.0	46.1	45.9	35.9	28.3	41.3	44.1	31.9	15.0	28.8	35.3	22.8	16.2	31.8	31.8	22.4
2002	9.2	31.8	50.4	28.8	12.2	42.1	69.8	38.9	6.5	27.2	44.3	24.3	9.1	34.1	60.2	32.1
2003	5.9	23.7	36.7	20.6	6.3	31.4	52.7	28.0	5.3	18.0	27.2	15.7	5.5	20.4	33.4	18.2
2004	11.0	22.0	35.8	20.9	11.0	22.2	44.6	22.6	10.8	21.7	32.9	20.0	11.0	20.4	37.5	20.2
2005	11.9	26.3	32.9	22.1	20.3	50.7	63.6	42.9	15.0	31.3	33.9	25.8	20.0	43.7	48.8	36.4
2006	3.2	9.0	22.3	10.2	4.8	17.0	45.2	20.4	3.5	11.8	23.0	11.1	5.0	18.2	38.7	18.6
2007	14.5	21.9	22.9	19.1	21.1	31.1	38.1	29.1	13.1	22.0	23.6	18.7	16.3	26.1	33.1	24.1
2008	8.7	13.7	18.6	12.0	9.6	15.5	22.1	13.9	10.6	15.3	19.1	13.4	10.5	15.8	19.8	13.4
2009	6.5	14.9	27.6	14.3	7.7	25.2	58.3	27.8	4.8	14.4	23.4	12.0	5.1	17.5	42.4	18.5
average	**10.3**	**21.6**	**30.6**	**19.1**	**12.5**	**28.9**	**46.4**	**26.9**	**8.7**	**19.6**	**27.5**	**17.0**	**10.1**	**23.8**	**36.7**	**21.4**

4. Summary and conclusions

The interpretation of the results can be specified in many directions, but the most important and obvious conclusions are listed as follows:

- Over the bigger, mostly flat part of the domain, the modeled values of the *SWE* are relatively close to the analysis. The BIAS here shows high spatial and temporal (i.e., from month-to-month and from season-to-season) variability, but generally the BIAS remains in the interval of (–10)–10 mm.

- The most significant discrepancies, mainly in direction overestimation (negative BIAS), are detected clearly over the Carpathian ridge, especially over the northern half.
- For all modcons the absolute value of the BIAS for February is greater than for the winter average, suggesting overall proportionality of the BIAS and the *SWE* values.
- The presented figures and *Table 1* do not outline any model configuration which output is clearly better/worse than the others.

Despite the high variability of the BIAS, even in adjacent gridcells, the detected negative BIAS for all modcons over the Carpathian ridge, especially over its northern part, seems systematic, and this is the main issue of this work. The comparison of the model results with the Globsnow product (*Chervenkov et al.,* 2016) shows significant dispersion of the BIAS, but also with prevailing negative values. Being the "final outcome" of complex atmospheric processes and interactions with the land surface, the snow cover can be influenced in many pathways along the simulation chain. Thus, for example, the relatively poor model performance in 2003 and 2010 can be rooted in the inadequate description of the large scale precipitation over the domain. Finally, the fact that the CARPATCLIM snow products are not pure observations suggests its possible deviation from the "truth state".

The model RegCM is constantly developed and, respectively, its simulation capabilities are steadily increasing. Further numerical experiments have to be performed, in particular including other parameterization schemes. The study confirms, however, that horizontal resolutions over 10 km are highly insufficient for regional snow cover modeling, especially over topographic heterogeneous terrain as the larger Carpathian Region. This fact have to be regarded by selecting the simulation tool and the model configuration. This is very important due to the fact that the mountainous snow covers are, generally speaking, those with the longest duration and thickness, with its all hydrological, ecological, and socio-economical consequences.

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