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RCM PERFORMANCE IN REPRODUCING TEMPERATURE AND PRECIPITATION REGIME IN ROMANIA. APPLICATION FOR BANAT PLAIN AND OLTENIA PLAIN

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Abstract: The main objective of this paper is to analyse three RCMs (RegCM3, CNRM and UCLM) regarding their performance in simulating the temperature and precipitation regime in Romania, with more details for two test areas (Banat Plain and Oltenia Plain). These results were obtained within the CC-Waters project (www.ccwaters.eu), where these RCM outputs have been used to estimate future temperature and precipitation changes for the two mentioned areas. The RCM performance has been firstly analysed in terms of their capability to reproduce the long term mean of the observed monthly temperature and precipitation over the current climate (1961-1990) in the two test areas, expressed by the mean error (bias). In the RCM validation, homogenized temperature and precipitation data as well as corrected precipitation for the two test areas were used. More details are shown for two RCMs (RegCM3 and CNRM) to understand the mechanisms leading to their errors in simulating the observed climate features. The large- scale variability of dynamic (sea level pressure) and thermodynamic (air temperature at 850 mb and specific humidity at 700 mb) climate variables are analysed. The RCM capability to reproduce the main state for these variables, as well as the main modes of their simultaneous variability (given by the first three EOF patterns), is analysed. Simultaneous variability of temperature and precipitation over the two test areas is also analysed. The NCEP grid point data are considered as observed large-scale climate variables. On annual scale, the RegCM3 is generally the most accurate in simulating the observed mean temperature at almost all stations; for the precipitation, the CNRM model is most accurate for the Oltenia Plain, while for Banat Plain the UCLM model is most accurate. However, there are differences on monthly scale. In terms of simultaneous variability of local and large-scale climate variables, the RegCM3 is also most skilful.

1. INTRODUCTION

Coupled Atmosphere-Ocean Global Climate Models (AOGCMs) are major tools to simulate the complexity of the climate system and to provide reliable projections of climate change in the future perturbed climate under various greenhouse gas emission scenarios. For simplicity of presentation, they are often called GCMs. Based on physical laws governing the climate system, these models constitute the most sophisticated mathematical simulators of the climate system, useful for our understanding of its natural variability and its response to changes in its forcing. Due to the complexity of the climate system and to the extended simulation periods required for their slow components (several centuries), these models are very demanding on computer resources, even on today's fastest super-computers. From these reasons, the AOGCMs are still integrated on coarse horizontal resolutions, now commonly a grid size of about 300 km at the equator. Some AOGCM simulations used a 125 km grid (IPCC, 2007). The AOGCMs are able to simulate fairly well the most important mean climate features on large scales, the upper-air fields being better simulated than surface climate variables. Among surface climate variables, large-scale sea level pressure (SLP) is usually better simulated, while the others, such as air temperature and precipitation, are not well simulated on smaller scales (Palutikof et al.; 1997, Busuioc et al., 1999, 2001).

Studies of environmental, social and economic impacts associated with anticipated climate changes demand spatially detailed information that is still rather impractical with today's AOCMs. Two techniques are used to generate information below the grid scale of AOGCMs (referred to as downscaling): dynamical and statistical. Dynamical downscaling uses high-resolution climate models to represent either global or regional sub-domains. These use either observed or lower resolution AOGCM data as their boundary conditions (Christensen et al., 2007). Statistical (or empirical) downscaling methods apply statistical relationships derived from observed data to climate model data. Dynamical downscaling has the potential for capturing mesoscale nonlinear effects and providing coherent information between multiple climate variables. These models are formulated using physical principles and they can faithfully reproduce widely varying climates around the world, which increases confidence in their ability to downscale realistically future climates. The main drawback of dynamical models is their computational cost. Also, in future climates the parameterisation schemes they use to represent sub-grid-scale processes may be operating outside the range they were designed for.

The dynamical approaches have been directed in two directions. One of them consists in improving of the GCM horizontal resolution up to T106 (about 1.125^{o}). Unfortunately, these simulations are quite costly and for climate change estimation the applications so far have been restricted to the "time slice modus" (Bengtsson et al., 1995) that uses an atmospheric high-resolution global model (AGCM) forced by the mean boundary conditions simulated in a low-resolution atmosphere-ocean coupled model, e. g. AGCMs include fully interactive land-surface processes as in an AOGCM but require information on sea surface temperatures and sea-ice (SSTI) as a lower boundary condition. Notable improvements occur in orographic precipitation and improved dynamics of mid-latitude weather systems (Christensen et al., 2007).

An alternative to uniform high-resolution is variable-resolution AGCMs (VRGCM; e.g., Déqué and Piedelievre, 1995). The VRGCM approach is attractive as it permits, within a unified modelling framework, a regional increase of resolution while retaining the interaction of all regions of the atmosphere. Numerical artefacts due to stretching have been shown to be small when using modest stretching factors (e.g., Lorant and Royer, 2001). VRGCMs results capture, over the high-resolution region, finer scale details than uniform-resolution models while retaining global skill similar to uniform-resolution simulations with the same number of grid points.

Other direction in dynamical downscaling is given by the limited area models (LAMs) or Regional Climate Models (RCMs) that are "nested" within a GCM) (Giorgi and Mearns, 1999; Giorgi et al., 2001). This technique, initially used for numerical weather prediction and then adapted for regional climate studies, presents some inconveniences given by the fact that the abrupt change of grid size at the lateral boundaries can distort wave propagation and reflection properties. Even if the RCMs seem to be the best tool in the future to estimate reliable regional climate changes they still need improvements in order to reduce the local systematic model errors. The RCM performance is dependent on the region and climate parameter of interest. Therefore, detailed analyses of the RCMs for various smaller regions are useful to estimate their reliability for future perturbed climate but this is not a sufficient condition.

This paper analysis the performance of three RCMs run in the ENSEMBLES project (van der Linden and Mitchell, 2009) in simulating the current climate conditions (temperature and precipitation over the period 1961-1990) in two test areas in Romania. In a previous study (Busuioc et al., 2006), the simulation data of winter precipitation in Romania completed with the ICTP regional model RegCM (Giorgi et al., 1993a, b; Pal et al., 2000) driven by lateral boundary fields from the Hadley Centre global atmospheric model HadAM3H (Jones et al., 2001) were analysed. It was found that the RegCM is more skillful then HadAM3H in the simulation of Romanian winter precipitation variability and its connection with large-scale circulations. However, because of its relatively coarse resolution (50 km), it still does not reproduce the complexity of the mechanisms controlling the local/regional variability induced by the topography.

The ENSEMBLE RCM simulations (van der Linden and Mitchel, 2009) used in the present study refer to improved versions of the previous RCMs run in the PRUDENCE project (Frei et al. 2006), with a spatial resolution of 25km. The performance of 9 ENSEMBLES RCMs in simulating the main characteristics of the current climate temperature and precipitation variability over the entire Romanian territory has been analysed by Busuioc et al. (2010). It has been found that, among others, the two RCMs analysed in this paper (RegCM3 and CNRM) are the most skilful on spatial average over the entire Romanian territory, in terms of temperature and precipitation annual average. These two RCMs and UCLM regional model are used in the present paper to perform a detailed monthly analysis over two smaller regions (Banat Plain and Oltenia Plain), as these regions were considered in the CC-WaterS project (www.ccwaters.eu) to develop climate change scenarios on local scale used in impact studies on water supply. Additionally, these two areas are very important from the agriculture point of view and, therefore, some stakeholders are interested how their main climate characteristics (temperature and precipitation) will be changed in the future. The estimation of the uncertainty associated to the RCM climate signal, includes, among other aspects, the RCM validation over the analysed area as it is presented in this paper. The data and methods are summarized in Section 2 and the results are presented in Section 3. Section 4 presents the main conclusions drawn from the present paper.

2. DATA AND METHODS

The observed data used to validate the RCMs includes the monthly mean temperature and monthly precipitation totals at 11 meteorological stations (Figure 1) and grid point monthly sea level pressure (SLP), geopotential heights at 500 mb (H500), air temperature at 850 mb (T850) and specific humidity at 700 mb (SH700), resolution of 2.5^o x 2.5^o from the NCEP-NCAR reanalysis (Kalnay et al., 1996). The areas between 30^o-55^o N and 5^o - 35^o E and the period 1961-1990 are considered for this analysis. The observed data sets were previously homogenized using the method presented by Szentimrey (1997) and precipitation data were additionally adjusted (Cheval et al., 2010) considering the physical-geographic factors (mainly wind speed and the share of solid precipitation). Details about the data homogenization and precipitation correction in Romania are presented by Busuioc et al. (2010), Cheval et al. (2010); therefore we do not go into details in this paper.

In a previous study, the RCM validation regarding the Romanian climate has mainly been made in a much more qualitative way (Busuioc et al., 2006). To have a reliable comparison with observations, a quantitative approach is proposed by Busuioc et al. (2010), based on a grid point observed data set with the same spatial grid as RCMs (25 km), which was achieved using the GIS technique applied to the highest density of observed data set representing seasonal long term means for temperature (96 stations) and precipitation (104 stations) over the 1961-1990 period. The comparison between the grid point RCM outputs and observed values has been made by using three statistics measuring the RCM performance: mean error (BIAS), root-mean squared error (RMS) and spatial correlation (COR). In this way, the RCM capability in reproducing the mean climate state as well as the spatial features is analysed. Analysing 9 RCMs achieved within the ENSEMBLES project (van der Linden et al., 2009), it was found that, as spatial average over Romania, almost all RCMs overestimate the seasonal temperature in Romania, the highest biases being produced by the two versions of the HIRHAM RCM (driven by ARPEGE and ECHAM5 GCMs). Considering all seasons, the most skilful RCMs are represented by the RegCM3-ECHAM5, CNRM-ARPEGE, REMO-ECHAM5, RACMO-ECHAM5 and SMHIRCA-ECHAM5, almost all being driven by the ECHAM5, except for the CNRM. As an example, Table 1a shows the results for RegCM3 and CNRM. Even if the spatial average over the Romanian territory of the grid point biases is almost zero (indicating a high RCM performance), in some cases, on smaller areas, the results could be different: higher values for one region and smaller ones (and opposite sign) for others (not shown). This result shows the importance of the detailed analysis on smaller areas as it is presented in the present paper.

The results are different for precipitation. Generally, the 9 RCMs overestimate the precipitation in all seasons, except for summer when it is underestimated. The CNRM and RegCM3 reproduce well the spatial precipitation distribution but, in wintertime, they show the highest overestimation (Table 1b).

In the present study, we go into more details on monthly scale for two smaller areas, Banat Plain and Oltenia Plain (see Fig. 1) by considering only three RCMs (RegCM3, CNRM and UCLM). The temperature and precipitation biases for the two areas are analysed in section 3.1. To understand the mechanisms leading some RCM errors in simulating the features of the regional/local Romanian climate (mentioned above), the large/regional scale variability of the main climate variables are analysed, such as: sea level pressure, geopotential heights at 500mb, air temperature at 850 mb and specific humidity at 700 mb. The RCM capability to reproduce the main state for these variables, as well as the principal modes of their simultaneous spatial variability (given by the first three EOF patterns), are analysed.

For the simplicity of presentation, the

Table 1. Performance of two RCMs (achieved in the ENSEMBLES project) analysed in this paper in simulating the long term mean (1961-1990) of the seasonal mean temperature and precipitation amount in Romania (spatial average): mean error (BIAS, ^{0}C for temperature and % for precipitation), root mean squared error (RMS), spatial correlation (COR). These values are derived from the RCM grid points (25 km resolution) against observations (homogenised data) interpolated in the same grid points using the GIS technique, over the area (20.125-30.125^{0}E, 43.375-48.375^{0}N) (from Busuioc et al., 2010).

Model (RCM)	**Winter**			**Spring**			**Summer**			**Autumn**		
	BIAS	**RMS**	**COR**	**BIAS**	**RMS**	**COR**	**BIAS**	**RMS**	**COR**	**BIAS**	**RMS**	**COR**
a) Temperature												
RegCM3-ECHAM5	1.6	2.1	0.82	-1.5	2.1	0.72	-1.2	1.9	0.84	-1.2	1.7	0.85
CNRM-ARPEGE	0.7	1.7	0.81	-1.3	2	0.71	2.9	3.3	0.76	-0.5	1.6	0.81
b) Precipitation												
RegCM3-ECHAM5	50	99	0.68	27	65	0.82	-27	81	0.76	34	74	0.78
CNRM-ARPEGE	59	120	0.71	15	60	0.79	-36	98	0.76	47	89	0.76

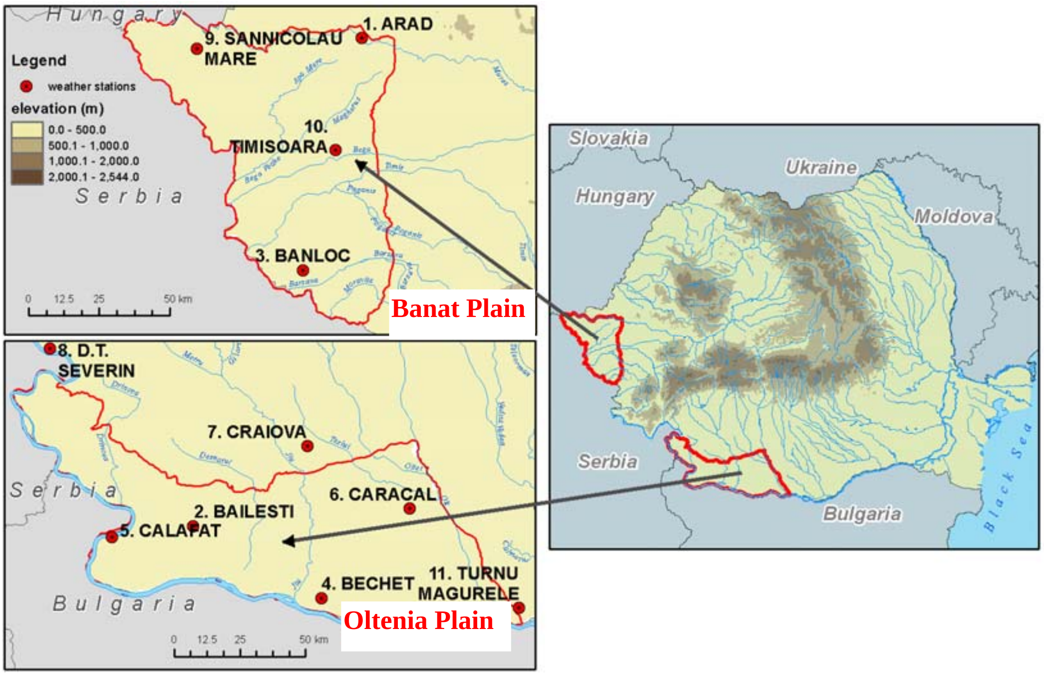


Figure 1. Location of the two test areas analysed in the CC-WaterS project: Banat Plain and Oltenia Plain. The stations placed in these areas are shown in details (left side).

EOF analysis is presented only for the combined standardized anomalies of T850, SLP and SH700 field and the RegCM3 and CNRM models. These two models have been used as input in statistical downscaling models developed within the CC-WaterS project to get estimations of future changes in monthly temperature and precipitation at station scale in the two test areas, using the three large-scale variables as predictors. This was an additional reason to analyse in more detail their performance in reproducing the large scale variability of these predictors.

The simultaneous variability of temperature and precipitation over the two test areas is also analysed. In this way, the RCM capability to reproduce the complex mechanisms controlling the regional climate variability is analysed that it is for the first time performed for the Romanian climate and, on our knowledge, for other European climates as well. The large scale NCEP grid point data are considered as observed climate variables. These results are presented in Section 3.2.

3. REZULTS

3.1. RCM performance in simulating the climate in Banat Plain and Oltenia Plain.

Temperature

The biases of the three RCMs mentioned above (CNRM, RegCM3 and UCLM) regarding the monthly mean temperature and precipitation for the period 1961-1990 at the 11 stations within the two test areas (Banat Plain and Oltenia Plain) have been calculated. These values are quite similar for almost all stations from the two test areas. As an example, the monthly biases for two stations representative for the Banat Plain (Timisoara) and Oltenia Plain (Craiova) are presented in Figure 2. Figure 3 shows the annual averages of the monthly temperature bias. The results show that the UCLM model underestimates mean temperature during the winter, spring and autumn months and overestimates it in summer months. For this model, the largest negative biases are recorded in March-April (up to -5.2^{0}C at Drobeta Tr. Severin and -5.1^{0}C at Timisoara, in March), while the highest positive biases are recorded in August for all stations (between 3^{0}C and 4.4^{0}C); the model is more accurate (monthly bias around 0^{0}C) in reproducing the mean temperature in June and December for the Oltenia Plain, while for Banat Plain, the September and January mean temperatures are better simulated. On annual average, the UCLM model underestimates the observed mean temperatures with values ranging between -1.8^{0}C (Drobeta Tr. Severin) and -0.3^{0}C (Calarasi).

The CNRM model overestimates the mean temperatures during winter and summer months (only the summer for Drobeta Tr. Severin and Timisoara stations) and underestimates them in the rest of the year. Among the three RCMs analysed here, this model shows the largest positive biases (maximum value of 4.8^{0}C at Banloc and Calafat stations in July), leading to an annual positive bias, generally exceeding 1^{0}C for almost stations within the two test areas. However, for some months, this model reproduces very well the observed mean values: March for the most number of stations (7), October for five stations, December for three stations, January and February for one station.

The annual mean temperature is better reproduced by the RegCM3 model for almost all stations, except for Drobeta Tr. Severin and Timisoara, when the

CNRM model is most accurate. However, on monthly scale, this model overestimates the observed mean temperatures in winter time and underestimates them in the rest of the year; these negative biases are balanced by higher positive biases during the winter, exceeding 3.0^{0}C at almost all stations in January (maximum of 4.5^{0}C at the Bechet station), leading to a bias around 0^{0}C on annual scale. Generally, the March mean temperature is most accurate simulated for all stations, especially for those within Oltenia Plain. For two stations within Banat Plain (Arad and Timisoara), the November mean temperatures are most accurate simulated, while for Banloc (Banat Plain) and Bechet (Oltenia Plain) July temperature are best reproduced.

In conclusion, from the temperature point of view, on an annual scale, among the three RCMs analysed in this paper, it could be summarized that the RegCM3 model is most accurate in simulating the observed values at almost all stations, except for Drobeta Tr. Severin and Timisoara when the CNRM model is most accurate.

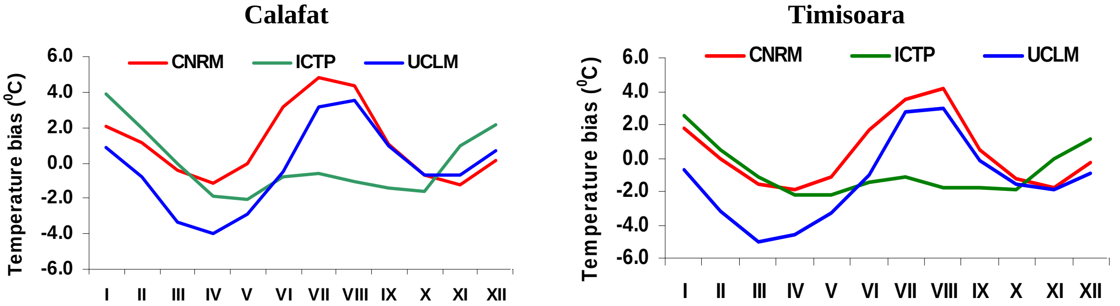


Figure 2. Monthly mean temperature bias of the three RCMs analysed in this paper, calculated for two representative stations: Calafat (Oltenia Plain) and Timisoara (Banat Plain).

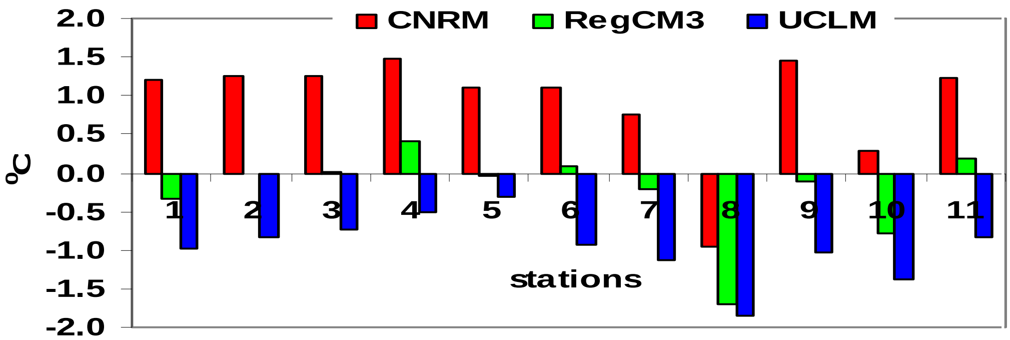


Figure 3. The annual mean temperature bias of the three RCMs analysed in this paper. The name and locations of stations are presented in Figure 1.

Precipitation

A similar analysis has been made for precipitation. The annual averages of the monthly precipitation biases at the 11 stations are presented in Figure 4 and an example of monthly biases for two stations, representative for the two test areas, is presented in Figure 5. The results show that, generally, the long term averages (1961-1990) of precipitation totals are overestimated for cold months and underestimated for warm months but the number of months with positive/negative biases is dependent on the RCMs. The most and highest magnitude of the overestimations are recorded by the RegCM3 model for all analysed stations, ranging between 7 and 10 months during the year (Figure 5. This model also shows the highest positive magnitudes of the biases, especially over the Banat Plain where the bias of 166% has been noted at the Arad station in January. This fact determines an overestimation on annual scale (between 4% and 67%), highest for the Banat Plain. For some months, the long term mean of observed precipitation amounts is well reproduced by RegCM3 model but in a different way for the two test areas: Banat Plain (July, August), Oltenia Plain (November, September).

In case of the CNRM model, the number of overestimations ranges between 6 and 9 months, the positive biases being balanced by the negative ones over the Oltenia Plain, determining a good performance on annual scale for this model. On monthly scale, the observed precipitation amount are well reproduced in June (Banat Plain) and January/November (Oltenia Plain). In the most of cases, the UCLM model underestimates the precipitation amount, especially over Oltenia Plain (about 8 months during the year) compared to Banat Plain (5 months during the year). This model recorded the largest bias at the Tg. Magurele station in Oltenia Plain (63%).

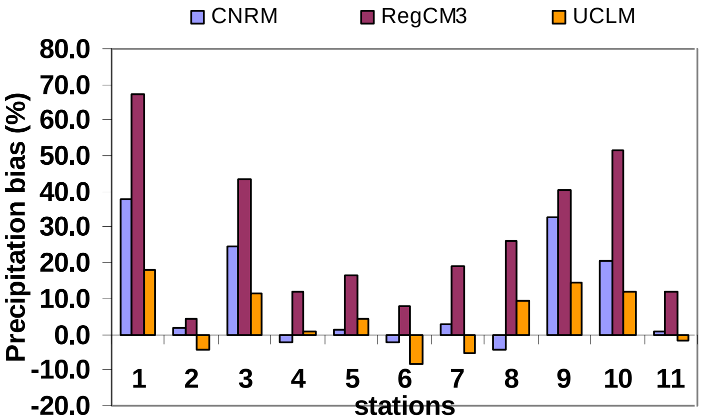


Figure 4. The annual average of the precipitation bias (%) of the three RCMs analysed in the CC-WaterS project. The name and locations of stations are presented in Figure 1.

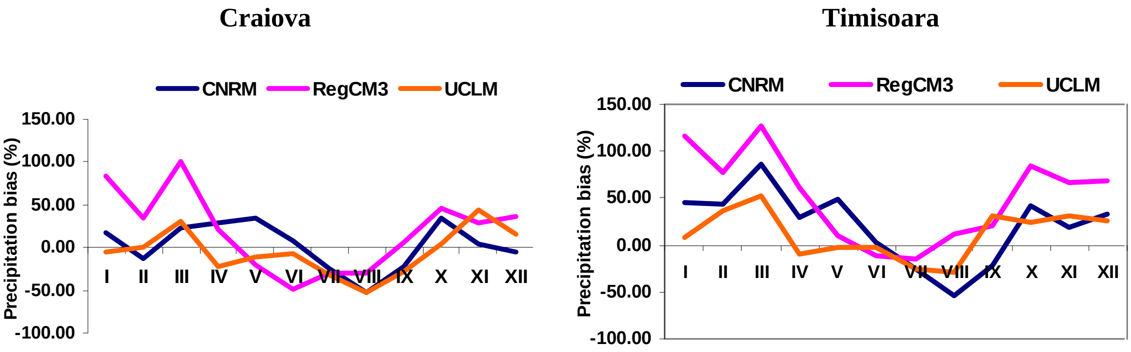


Figure 5. Monthly precipitation bias of the three RCMs analysed in the CC-WaterS project, calculated for two representative stations: Craiova (Oltenia Plain) and Timisoara (Banat Plain).

It could be concluded that, from the three RCMs analysed in this paper, the CNRM model is most accurate in simulating the observed annual precipitation amount for Oltenia Plain, while for Banat Plain the UCLM model is most accurate.

3.2. RCM performance in simulating large/regional scale variability.

3.2.1. Temperature and precipitation variability in Banat/Oltenia Plains.

To understand the RCM performance in simulating the simultaneous variability of temperature and precipitation in Banat and Oltenia Plains, the first two EOF patterns of the combined standardized anomalies of temperature and precipitation at the 11 stations in the two test areas were computed and compared to those derived directly from the grid point data of the two RCMs. The components of the EOF patterns are quite homogeneous for the two test areas. From this reason and for the simplicity of presentation, the EOF spatial averages over the two test areas were computed and the results are presented in Table 2, as example for winter and summer.

It can be seen that the principal mode of the observed simultaneous temperature and precipitation variability (EOF1), explaining 52% from the total observed variance for winter and 54% for summer, show opposite variability between temperature and precipitation for both test areas and both seasons, with a little higher variability for the Oltenia Plain. This characteristic is well reproduced for both seasons by the RegCM3, while the CNRM reproduces it only for summer; for the winter season this model show same sign of variability, similar to the observed EOF2 pattern. In terms of the explained variance, the two RCMs overestimate it for summer (e.g. u 63-64% vs. 54%). The magnitude of the precipitation anomalies are underestimated in winter by the both RCMs for Oltenia Plain and only by RegCM3 for the Banat Plain. In summer, the CNRM overestimates the precipitation anomalies for both test areas, while the RegCM3 overestimates it a little only for the Banat Plain.

The second mode of the observed

Table 2. The components of the first two EOF patterns (standardized anomalies), averaged over the two test areas, computed from the combined temperature and precipitation standardized anomalies over the period 1961-2007. These values are presented separately for temperature and precipitation.

Obs./ Models	EOF 1					EOF 2				
	var (%)	Patterns				var (%)	Patterns			
		Oltenia		Banat			Oltenia		Banat	
		Temp.	Precip.	Temp.	Precip.		Temp.	Precip.	Temp.	Precip.
Winter										
Obs.	52	0.8	-0.8	0.7	-0.6	31	0.5	0.5	0.6	0.7
RegCM3	54	0.9	-0.4	0.9	-0.4	20	0.4	0.7	0.3	0.8
CNRM	55	0.9	0.5	0.9	0.6	32	-0.4	0.7	-0.4	0.6
Summer										
Obs.	54	0.9	-0.6	0.8	-0.4	20	0.2	0.6	0.4	0.5
RegCM3	63	0.9	-0.6	0.9	-0.6	18	0.3	0.5	0.3	0.4
CNRM	64	0.8	-0.8	0.8	-0.8	25	0.5	0.5	0.5	0.5

variability (EOF2), explaining 31% from the total observed variance for winter and 20% for summer, show same sign of variability for temperature and precipitation for both test areas and both seasons. This characteristic is well reproduced again by the RegCM3 and only for the summer season by the CNRM. In terms of the explained variance, the RegCM3 underestimates it for winter, while the CNRM slightly overestimates it for summer. In terms of the magnitude anomalies, the observations show a higher variability for summer precipitation (vs. temperature) in the case of Oltenia Plain and a higher variability of summer temperature anomalies in Banat Plain (vs. Oltenia Plain). The first feature is well reproduced only by the RegCM3. The CNRM model overestimates the summer temperature for the Oltenia Plain, while the RegCM3 underestimates the winter temperature anomalies for the Banat Plain.

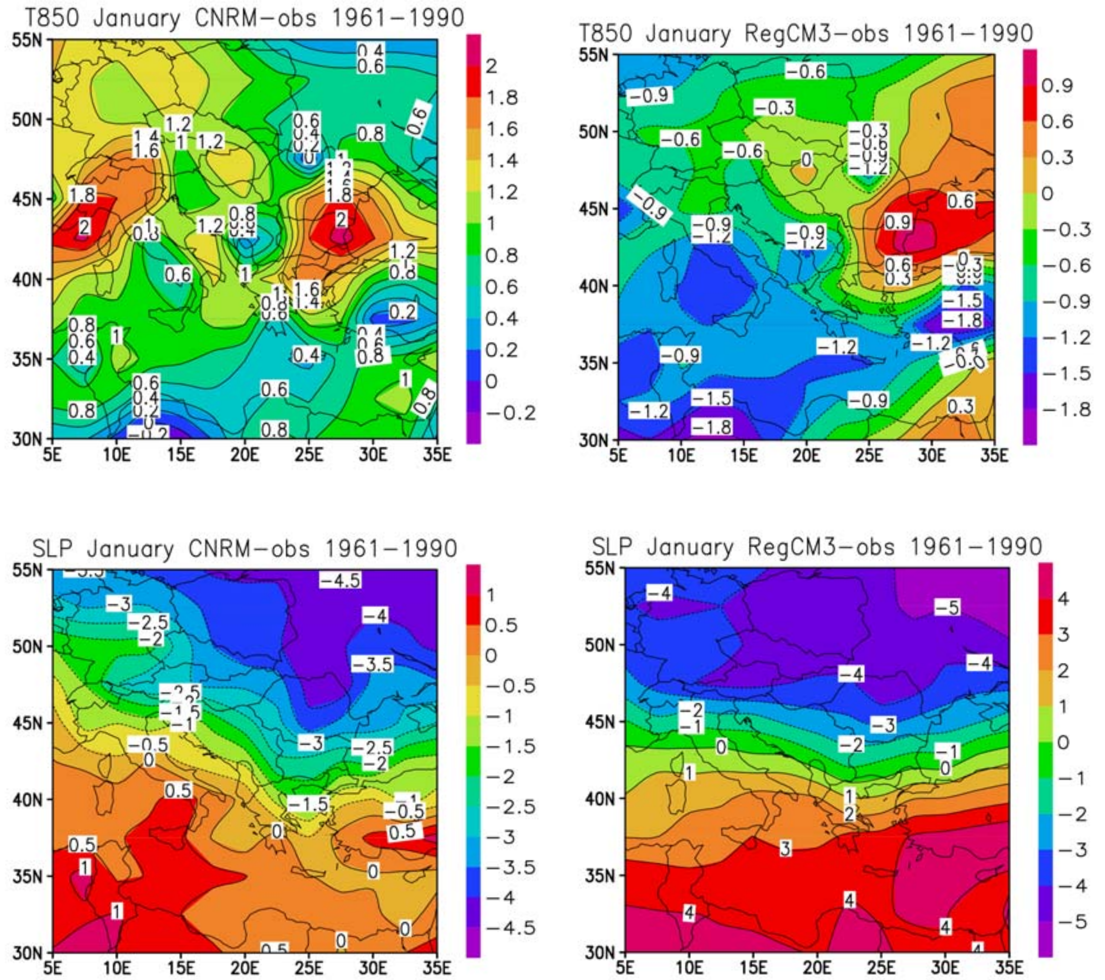
The results presented above show more details of the RCM error in simulating the simultaneous variability of temperature and precipitation over the two test areas.

For understanding the reasons leading to the RCM errors in simulating the features of the regional/local Romanian climate revealed in Section 3.1., the large-scale variability of the main climate variables were analysed, such as: sea level pressure (**SLP**), geopotential heights at 500 mb (**H500**), air temperature at 850 mb (**T850**) and specific humidity at 700 mb (**SH700**). The RCM capability to reproduce the main state for these variables (long-term mean for the current period 1961-1990), as well as the modes of their combined spatial variability (given by the first three EOF patterns), were analysed. Some characteristic months for each season were considered: January, March, July and September. It has been found that, for all these months, the CNRM model strongly underestimates the H500 field. The RegCM3 model overestimates it in July and underestimates in the rest of months. The T850 biases are generally in agreement with the temperature biases over the two analysed areas (e.g. same sign) that is agreement with the results presented by Busuioc et al. (2010) for the entire Romanian territory, when the connection between the temperature in Romania and large-scale T850, SLP and SH700 is analysed using the canonical correlation analysis (CCA). As it has been presented in this paper (Busuioc et al., 2010), for the winter season, the surface temperature variability is also influenced by the surface circulation (e.g. SLP variability). The SLP is underestimated by the both RCMs in January and March (e. g. more frequent cyclonic structures over the analysed area) and overestimated in July and September (e.g. more frequent anticyclonic structures). This result is in agreement with the precipitation underestimation/overestimation (see Section 3.1): more precipitation in January for both RCMs could be explained by more frequent cyclonic structures; for July more frequent anticyclonic structures explain the precipitation deficit simulated by both RCMs in this month. The mechanisms controlling the precipitation variability are more complex, especially in the summertime when the moisture plays an important role (Busuioc et al., 2010).

The detailed explanations for two representative months for winter (January) and summer (July) are presented bellow.

Figure 6 shows the T850 and SLP biases of the two RCMs (CNRM and

RegCM3) for January. The T850 is strongly overestimated by the CNRM over the entire Romania, while the RegCM3 overestimates it over the southern and southeastern part (including Oltenia Plain) and reproduces it quit well over the Banat Plain. This result explains very well the temperature overestimation in January for both test areas by the CNRM model and for the Oltenia Plain by the RegCM3 model. The pattern of the RegCM3 SLP bias suggests an overestimation of the cyclonic structures over Romania induced by the zonal circulations, leading to overestimation of the Atlantic warm and wet air mass transport affecting especially the Banat Plain (due to the Carpathian topography) that explains the warm and wet climate over Romania. The overestimation of the cyclonic structure over the entire Romania by the CNRM model (negative SLP biases) explains also the overestimation of precipitation over the two test areas.


T850 January CNRM−obs 1961−1990

T850 January RegCM3−obs 1961−1990

SLP January CNRM−obs 1961−1990

SLP January RegCM3−obs 1961−1990

Fig. 6 Biases (against NCEP reanalysis) of the T850 and SLP in January derived from the simulations of CNRM (left column) and RegCM3 (right column) over the current period 1961-1990.

To analyse the RCM capability to reproduce the main modes of the combined variability of dynamic (SLP) and thermodynamic (T850, SH700) climate variables, the first three EOF patterns of their combined standardized anomalies are analysed. Figure 7 shows these patterns for January, presented individually for each variable, derived from observations (reanalysis). These patterns show the coherency between the simultaneous spatial variability of the three climate variables. The induced mechanisms could be summarized as follows:

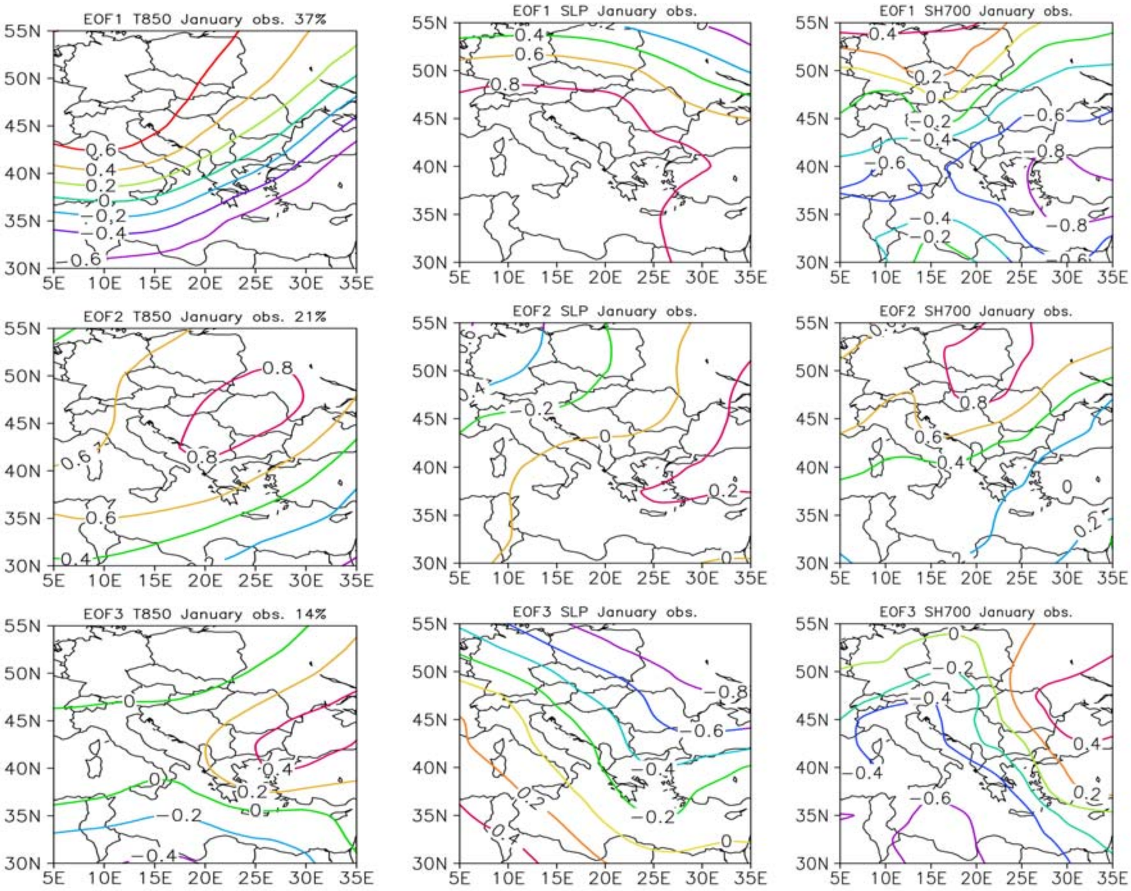


Figure 7. The patterns of the first three EOFs for the combination of standardized anomalies of January T850, SLP and SH700, as derived from the observed data (NCEP reanalysis, 1961-1990). The fraction of the respective total variance explained by each EOF is presented on the left column.

a) the main mechanism given by the EOF1 patterns explaining 37% from the total observed variance, associates a dipole T850 anomaly structure oriented from north-west to south-east (with Romania placed in a positive/negative area), with a surface anticyclonic/cyclonic structure centered over the eastern Mediterranean Sea) and a negative /positive SH700 anomaly structure over Romania (N-S gradient); **b)** second mechanism given by the EOF2 patterns explaining 21% from the total observed variance, suggests a simultaneous presence of a positive/negative T850 anomaly structure centered over Romania, with a surface meridional circulation (southerly/northerly direction, deviated due to the Carpathian topography) and a positive/negative SH700 anomaly structure over Romania (centered over northwestern part); this mechanism is very important for explanation the mechanisms controlling the Romanian climate, in general, and particularly for the two test areas, namely the influence of the Carpathian topography; **c)** EOF3 patterns accounting for 14% from the total observed variance, suggest a simultaneous presence of a low magnitude positive/negative T850 anomaly structure over Romania placed between two negative areas, a northwesterly/southeasterly circulation and a dipole structure of SH700 anomalies (Romania mainly placed in an area covered by positive values including the Oltenia Plain and the Banat Plain being included in an area covered by opposite sign of anomalies).

The mechanisms presented above show, generally, that the large area SLP anomalies are associated with SH700 anomalies with opposite sign (especially over the Romanian territory), with some discrepancies regarding the magnitude of the covered surfaces. The T850 variability is not generally connected to the variability of the other two variables. Similar figures are presented for the RegCM3 and CNRM, respectively (see Figures 8, 9). Generally, the RegCM3 reproduces the best the EOF patterns for all variables mentioned above (including the type of simultaneous variability and explained variance for EOF1 and EOF3) in January, except for EOF3 where some discrepancies can be revealed (compare Figures 7, 8). However, the overestimation of the explained variance for the EOF2 patterns (28% from RegCM3 against 21% from observations) could lead to overestimation of the frequency of the mechanism presented at b), *mainly more frequent T850 patterns with large positive anomalies over Romania, associated with large positive SH700 anomalies (with values higher than the observed ones) and southwesterly circulation that could explain more frequent warm and wet weather conditions over Romania in this month* (more details about these explanations are presented by Busuioc and von Storch, 1996; Busuioc et al., 2010 and Busuioc et al., 1999, 2001). Therefore, this model reproduces quite well the observed mechanisms of simultaneous variability between the three climate variables but some mechanisms are more frequent, leading to the RegCM3 errors in reproducing the observed climate features as presented above.

The CNRM model does not reproduce well the EOF patterns **(**compare Figs 7 and 9**)** and, in some cases, even the coherency between the simultaneous variability of the three parameters is not correctly reproduced (Figs 7, 9: EOF1 SLP and EOF1 SH700 show same sign in Fig. 9 comparing to observations in Fig. 7) or the importance of some patterns (given by the variance explained by the EOF patterns) is reversed compared to observations (e.g. EOF1 patterns of T850 and SH700 from the CNRM simulations are similar to corresponding EOF2 patterns from observations that means different explained variance comparing with observations: 38% in CNRM simulations (EOF1) against 21% from observations (EOF2)). Following the explanation presented above for the RegCM3, this result could lead *to an overestimation of the frequency of large positive T850 and SH700 anomalies, explaining the warmer and wetter climate conditions of January in CNRM simulations*. The SLP EOF1 and EOF2 patterns are quite similar to each other and to SLP EOF1 from observations. For July, the biases of the T850, SLP and SH700 are presented in Figure 10. The T850 is overestimated by the CNRM and underestimated by the RegCM3, explaining the temperature overestimation by the CNRM and underestimation by the RegCM3, respectively.

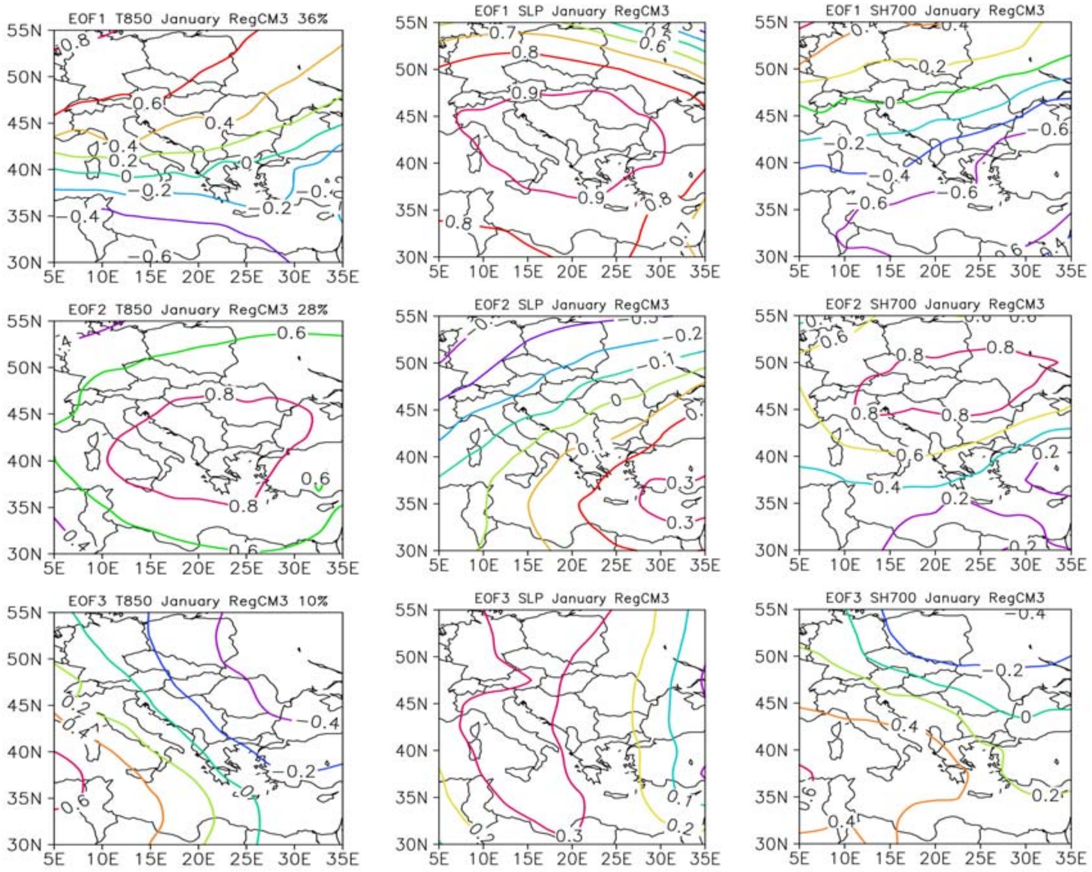


Figure 8. The patterns of the first three EOFs for the combination of standardized anomalies of winter T850, SLP and SH700 as derived from the RegCM3 simulations (1961-1990). The fraction of the respective total variance explained by each EOF is presented on the left column.

The SLP is overestimated by both RCMs (e.g. overestimation of the anticyclonic structures over Romania that generally are associated with less precipitation) that could explain the underestimation of precipitation for the two test areas. In case of the RegCM3, this conclusion is additionally supported by the SH700 underestimation, while the CNRM overestimates it.

As it was presented for January, to see how the two RCMs reproduce the coherency between the simultaneous spatial variability of the three climate variables, the first three EOF patterns of their combined standardized anomalies in July were analysed (not shown). The observed EOF patterns are generally different from those observed for January.

The mechanisms of simultaneous variability between SLP and SH700 are also changed, showing the same sign of variability between them for EOF2 and EOF3 and opposite sign for the EOF1 patterns that is similar to results presented for January. The T850 variability shows different sign compared to the SLP variability for EOF1 (similar to January) and the same sign for EOF2/EOF3. These mechanisms are quite well reproduced by both RCMs but the patterns are different, except for some cases: SLP EOF1 reproduced well by both RCMs, SH700 EOF2 reproduced well by the CNRM, T850 EOF1/EOF2 reproduced quite well by the RegCM3, with minor differences.

4. Conclusions

This paper presents useful techniques of analysis the RCM performance on regional/local scale such as: statistical indices for quantitative analysis of the RCM performance in simulating mean

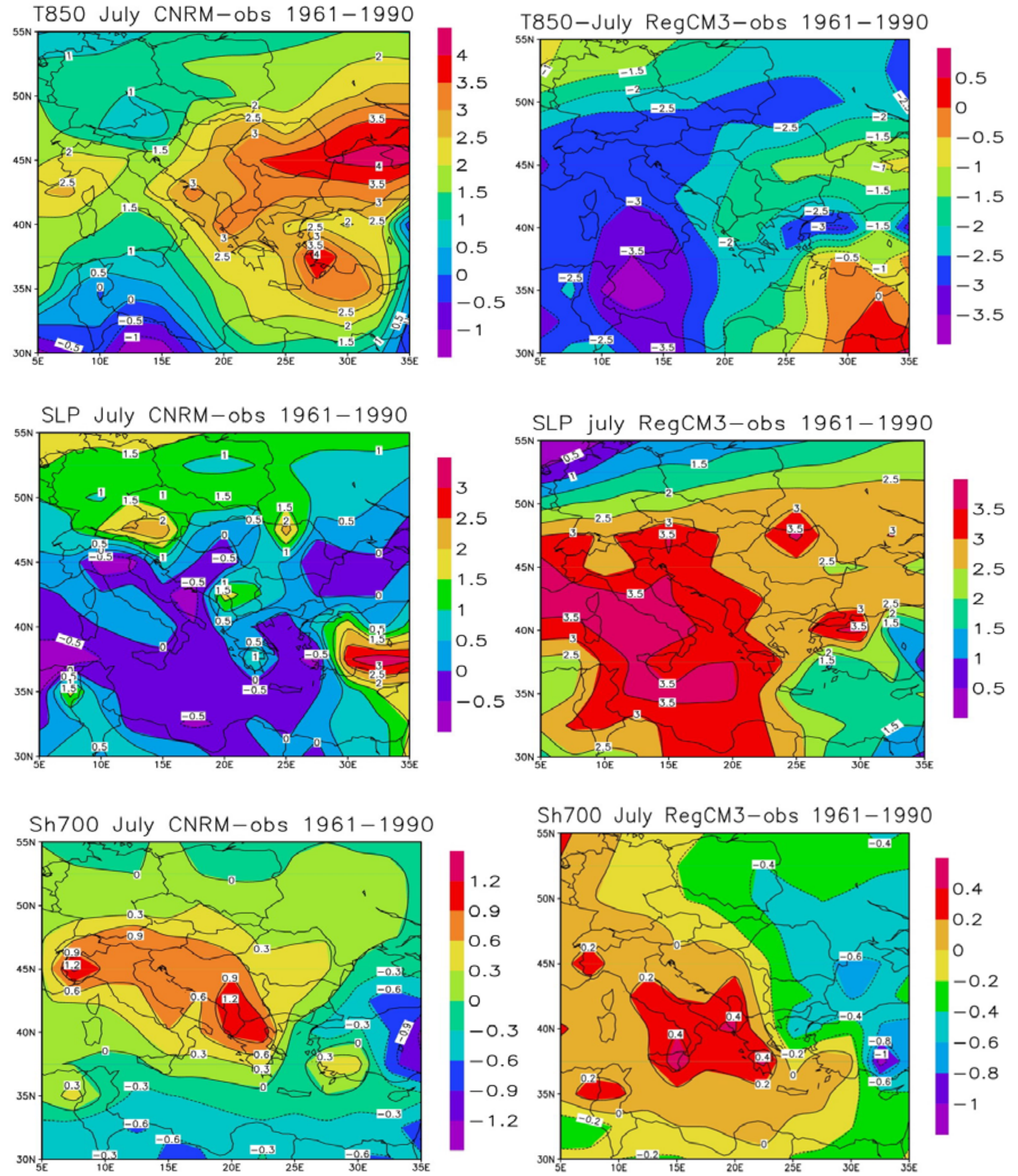


Figure 10. Biases (against NCEP reanalysis) of the T850, SLP and SH700 in July derived from the simulations of the CNRM (left column) and RegCM3 (right column) over the current period 1961-1990.

state (bias); EOF analysis of simultaneous variability of dynamic and thermodynamic variables at various levels and the simultaneous variability of observed temperature and precipitation on regional scale, to analyse the RCM capability to reproduce the real complex mechanisms of the large/regional scale climate variability to better understand the RCM errors in simulating the simultaneous variability of the observed temperature and precipitation variability. On our knowledge, this type of analysis of the combined climate variables in analyzing the RCM performance is for the first time presented for the Romanian climate as well as for other European climates.

The analysis was focused on two small test areas (Banat and Oltenia Plains), used in the CC-WaterS project to produce climate change scenarios. The performance of three RCMs (RegCM3, CNRM and UCLM) in reproducing monthly mean temperature and precipitation of the two test areas is analysed in more details. It was found that, among 9 RCMs derived within the ENSEMBLE project, on average over the Romanian territory and on annual scale, the RegCM3 and CNRM are between the most skilful ones, even if on monthly scale there are some errors. For the two test areas, the results can be summarized as following:

- The annual mean temperature is better reproduced by the RegCM3 model for almost all stations, except for Drobeta Tr. Severin and Timisoara, when the CNRM model is most accurate. However, on monthly scale, this model overestimates the observed mean temperatures in winter time and underestimates them in the rest of the year; these negative biases are balanced by higher positive biases during the winter, exceeding 3.0^0C at almost all stations in January, leading to a bias around 0^0C on annual scale.
- From precipitation point of view, among the three RCMs analysed within the CC-WaterS project, the CNRM model is most accurate in simulating the observed annual precipitation amount for Oltenia Plain, while for Banat Plain the UCLM model is most accurate. The results show that, generally, the long term averages (1961-1990) of precipitation totals are overestimated for cold months and underestimated for warm months but the number of months with positive/negative biases is dependent on the RCMs. The most and highest magnitude overestimations are recorded by the RegCM3 model for all analysed stations, this model showing the highest positive magnitudes of the biases. This fact determines an overestimation of the annual precipitation amount. In case of the CNRM model, the positive biases are generally balanced by the negative ones over the Oltenia Plain, determining a good performance on annual scale for this model. In most of cases, the UCLM model underestimates the precipitation amount, especially over the Oltenia Plain.

To better understand the reasons of the RCM errors presented above, as examples, the RegCM3 and CNRM capability in reproducing the features of large/regional scale variability over the current period 1961-1990, given by the first three EOF patterns, were analysed. It was found that the RegCM3 is more accurate in simulating the first two modes of the simultaneous temperature and precipitation variability over the two test areas. In the CNRM simulations, the order of the two EOF patterns are reversed (due to the differences in the explained variance), leading to an overestimation/underestimation of the importance of one pattern against the other as compared to observations.

The analysis of the first three EOF patterns of the combined standardized SLP, T850 and SH700 anomalies for two representative months for winter (January) and summer (July) shows the following conclusions: for January, in general, the RegCM3 correctly reproduces the observed mechanisms of simultaneous variability for the considered dynamic and thermodynamic variables in current climate conditions (1961-1990) but some of them are more frequent, leading to the overestimations of their mean state (long term mean); the CNRM does not reproduce well both these mechanisms and the importance of some of them. For July, these mechanisms are quite well reproduced by both RCMs but the patterns are different as compared to observations, except for some cases.

These RCM errors could justify the biases in the mean state of the three large-scale climate variables leading to temperature and precipitation biases in the two test areas, such as: in January, the overestimation of the T850 (higher for CNRM) and cyclonic structure over Romania explains warmer and wetter climate conditions simulated by both RCMs; in July, the T850 is overestimated by the CNRM and underestimated by the RegCM3, explaining the temperature overestimation by the CNRM and underestimation by the RegCM3, respectively; the anticyclonic structures over Romania is overestimated by both RCMs that could explain the underestimation of precipitation for the two test areas. These errors of the two RCMs analysed in this paper could be inherited from the driving global “mother” models but this aspect is not analysed in this paper. Additional arguments in understanding the reasons of the RCM errors in reproducing observed regional/local conditions could be obtained from the analysis of their performance in reproducing the connection between the local climate and large-scale predictors as presented in previous papers (e. g. Busuioc et al., 1999, 2001, 2006). These two aspects will be analysed in a future paper dealing with the statistical downscaling models driven by the two RCMs (manuscript in preparation).

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