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Izvorni znanstveni rad

REDUCING WARM BIAS OVER THE NORTH-EASTERN EUROPE IN A REGIONAL CLIMATE MODEL

Ublažavanje pogreške u temperaturi na području sjevero-istočne Europe u regionalnom klimatskom modelu

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Abstract: Large warm bias in near-surface temperature during winter was detected over north-eastern Europe in simulations with RegCM4 regional climate model when compared to observational dataset. Modifications to alleviate warm bias included reductions of the low-level cloud cover fraction and the minimum turbulent mixing in stable planetary boundary layer. When implemented, these modifications reduced warm bias up to 50% and did not degrade, or substantially impact, the variables analyzed outside the region and season considered. Validations of the planetary boundary layer and cloud features were limited due to unavailability of appropriate observational data at climatological timescales.

Keywords: regional climate model, cloud cover, planetary boundary layer, temperature bias

Sažetak: U simulacijama regionalnim klimatskim modelom RegCM4 uočena je, u usporedbi s mjerenjima, znatna pozitivna pogreška u prizemnoj temperaturi zimi u sjeveroistočnoj Europi. Promjene u modelu koje su ublažile tu pogrešku uključuju smanjenje udjela niske naoblake i minimalnog turbulentnog miješanja u stabilnom planetarnom graničnom sloju. Na taj način pogreška u temperaturi smanjena je do 50%, a da testirane promjene nisu pogoršale ili izraženo utjecale na analizirane varijable izvan područja i sezona od interesa. Ispitivanje valjanosti simuliranih svojstava planetarnog graničnog sloja i naoblake bilo je ograničeno zbog nepostojanja prikladnih mjerenja na klimatološkoj vremenskoj skali.

Ključne riječi: regionalni klimatski model, naoblaka, planetarni granični sloj, pogreška u temperaturi

1. INTRODUCTION

Regional climate models (RCMs) are used to simulate and predict climate on regional spatial scales. Their most common application is dynamical downscaling of global climate/circulation models (GCMs) simulations or global (re)analysis datasets (e.g. Kjellström et al. 2011). While steadily improving over the last 20 years, the theory and practice behind RCMs are still developing (e.g. Giorgi and Mearns 1999, Laprise et al. 2008).

The accuracy of simulated as well as predicted near-surface temperature (T2m) climate and variability is very important in RCMs due to its direct impact on human activities. In the regional climate model RegCM4, used in this study, a relatively large warm bias in T2m is detected during winter (December-January-February, DJF) over the high-latitude Subarctic part of Europe. The occurrence of similar warm bias over the same region and in the same season was recently documented in other models too. In the EC-Earth[1] GCM, the warm bias was found to be connected with errors in simulating snow cover (Hazeleger et al. 2010). In the RCA3[2] RCM, warm bias was detected over the same area and with almost

[1] GCM based on European Centre for Medium-Range Weather Forecasts model and developed by the EC-Earth consortium, KNMI, the Netherlands.
[2] Rossby Centre Regional Climate model version 3, Rossby Centre, SMHI, Sweden.

identical amplitude as in RegCM4 (Samuelsson et al. 2011). It was also associated with the simulation of snow related processes. Krichak (2008) attributed similar warm bias in RegCM3 (an earlier version of the RegCM model) to the model's low spatial resolution used in his integrations, which would have had an adverse impact on large-scale circulation and advection of cold air.

In this study, it is assumed that origins of warm bias are linked to local processes rather than being associated with large-scale flow. Local processes, in turn, are studied by diagnosing radiation balance, which in the Subarctic area during DJF is highly influenced by downward longwave radiation from the clouds and the atmosphere (e.g. Przybylak, 2003). The components of radiative balance are, together with large-scale advection of warmer air, the source of energy for this cold region. Low surface temperatures support formation of stable and shallow planetary boundary layers. The third important feature of the Subarctic includes the formation of large and long-lived snow-covered areas. Having in mind the importance and impact of this region on climate of the mid-latitudes, realistic simulations of present climate over the high-latitudes are required as an important precondition to use GCMs and RCMs as effective tools for the prediction of the 21st century climate (e.g. Sorteberg et al. 2007).

The aim of the study is to present and discuss this bias in RegCM4 and to offer potential solution for its alleviation. In order to ascertain causes of warm bias in RegCM4, two hypotheses are tested in this study: (1) RegCM4 overestimates total cloudiness over the specific area during DJF i.e. the increased cloudiness is, via cloud emissivity, associated with an increased longwave radiative forcing; (2) RegCM4 overestimates turbulent mixing in the planetary boundary layer (PBL) during DJF, that is, a stronger turbulent mixing and potentially increased height of PBL can be associated with an increased heat capacity of the lowest part of the atmosphere, as discussed for an idealized framework by e.g. Esau and Zilitinkevich (2010). The above hypotheses cannot be tested directly because the appropriate global validation datasets are not readily available. Seidel et al. (2010), for example, pointed out to the need of a uniform global climatology of PBL height which would be based on measurements. In their analysis, they computed PBL height from vertical soundings in various ways and detected several sources of uncertainties that have caused the height of PBL to vary up to few hundred meters. In addition, Li et al. (2008) found substantial differences between the cloud-related variables in satellite observations, reanalysis and global models. Therefore, our simulations are compared with the corresponding ERA-Interim reanalysis fields (Simmons et al. 2006) or with the different RegCM4 model versions. Though the height of PBL can be defined in various ways (e.g. Zilitinkevich and Baklanov 2002), in both RegCM4 and ERA-Interim it is diagnosed as the height where the bulk Richardson number equals the critical Richardson number 0.25. Thus, there is a level of comparability for this variable between the two different datasets.

The structure of the study is as follows. Section 2 (Method) describes four numerical experiments and motivations behind them. Section 3 (Results and discussion) describes and interprets the impacts of applied modifications on climatology of surface fields and vertical profiles of the cloud-related variables. Section 4 (Summary and conclusions) summarizes main results and closes the study.

2. METHOD

Regional climate model RegCM4 with the 50-km grid spacing is used to downscale ERA-Interim reanalysis available at the 1.5°x1.5° longitude/latitude resolution for the 5-year period, 1 January 1989 to 31 December 1993, over the European/north African domain centred at 48°N, 9.75°E. Details of the earlier version, RegCM3, are given in Pal et al. (2007), while RegCM4 was still under development at the time of writing. The differences between RegCM3 and RegCM4 are mainly technical rather than in physical parameterizations or in model numerics. Parameterizations of unresolved physical processes include: the BATS scheme for land surface processes (Dickinson et al. 1993), the Holtslag et al. (1990) nonlocal first-order scheme for PBL, the Pal et al. (2000) definition of large scale precipitation, the Grell (1993) scheme for convective precipitation with the Arakawa and Schubert (1974) closure and the scheme for radiation transfer from Kiehl et al. (1996).

Table 1. Description of the model experiments.

Tablica 1. Opis eksperimenata modela.

Model experiment	Vavrus and Waliser (2008) low-level cloud cover modification	Minimum vertical turbulent mixing reduced
DEF	No	No
PBL	No	Yes
CLD	Yes	No
FIN	Yes	Yes

The issue of large amount of low-level cloudiness at the high-latitudes in atmospheric models was raised by e.g. Vavrus and Waliser (2008). They detected an overestimation of the low-level cloudiness in CCSM3[3] GCM where, as in RegCM4, cloud cover fraction is a diagnostic variable calculated in terms of relative humidity. For comparison, in ERA-Interim reanalysis, cloud cover fraction at each model level is a prognostic variable. Vavrus and Waliser (2008) assumed that in the high-latitude regions during DJF, due to a low water vapour mixing ratio and scarcity of the cloud condensation nuclei, the expressions used to diagnose cloud cover in CCSM3 GCM are not valid, primarily because they were based on the data mostly from the tropical and mid-latitude regions. Their modification consists of a reduction of a fraction of the grid cell covered with clouds at levels lower than 750 hPa for cases when specific humidity falls below 0.003 $kgkg^{-1}$. Although they stressed that both thresholds are tunable, for the purpose of this study it was decided to keep modification in its original form.

It was found by Cuxart et al. (2006) that many operational and research PBL schemes generally overestimate turbulent mixing. Such an overestimation is associated with too deep PBL and the ensuing problem is whether the near-surface winds are then reproduced adequately. Since the RegCM4 PBL scheme could be influenced by similar type of errors, the second hypothesis is tested by allowing lower values of the turbulent mixing coefficients for heat, momentum and moisture than specified in the original model definition - in stable and neutral conditions, they are allowed to equal to zero.

Four different experiments were made: (1) the default run with the working version 1569 of the model[4] (denoted as DEF); (2) the run with the same modification in cloud cover, as in Vavrus and Waliser (2008; denoted CLD); (3) the run with modification in PBL (PBL); (4) the final run with modifications in both cloud cover and PBL (FIN). Table 1 summarizes all four model experiments. The length of integrations in the experiments with modifications was the same as in DEF, from 1 January 1989 to 31 December 1993. Validation of the simulated T2m is done by comparing with CRU T2m dataset (New et al. 2002, Mitchell and Jones 2005) after interpolating model data to the CRU grid; other fields are compared for the same variable across different experiments or against ERA-Interim reanalysis. Such a direct comparison of RegCM4 simulations allows an easier interpretation of the results, thus avoiding possible errors in measurement or differences in parameter definitions.

Whilst modifications of low-level cloudiness and vertical mixing include least interventions into the model code, they do retain a level of physical reasoning. More physical and advanced alternative methods would include e.g. prognostic cloud microphysics and PBL schemes.

3. RESULTS AND DISCUSSION

Figure 1 depicts the DJF T2m and the bias, averaged over five years, in the DEF experiment. There is a cold bias over the southern part of the domain, but largest warm differences, up to +8°C, are above the north-eastern part of the domain. In other seasons cold bias dominates all over the domain (not shown, but see, for example, Branković et al. 2011 results

[3] Community Climate System Model version 3, National Center for Atmospheric Research, Boulder, CO, USA.

[4] Available from http://eforge.escience-lab.org/gf/project/regcm/.

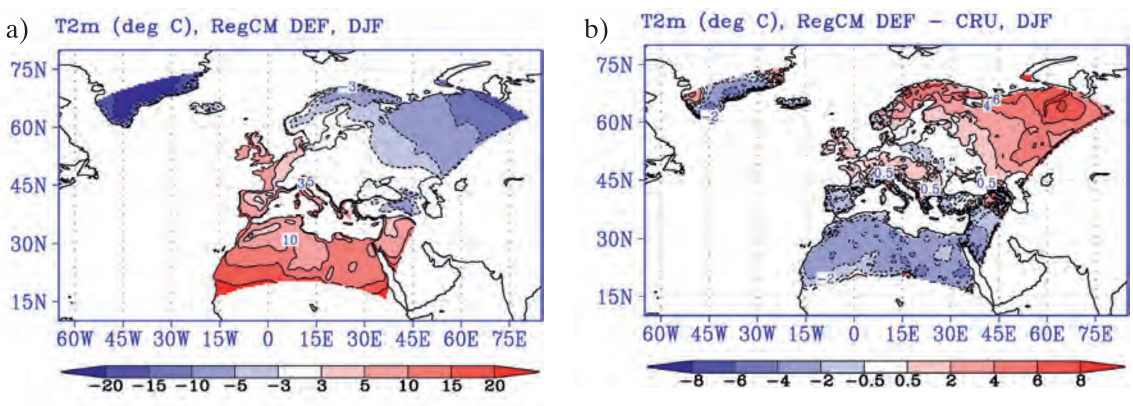

Figure 1: a) RegCM4 winter mean T2m and b) T2m bias when compared to CRU.

Slika 1: a) Srednja T2m zimi simulirana s RegCM4 i b) pogreška temperature prilikom usporedbe s CRU.

for RegCM3), except during SON when the warm bias with a smaller amplitude than in DJF is detected over the same region.

A random overlapping method is used in RegCM4 radiation parameterization to calculate cloud radiative forcing. Total cloudiness in RegCM4 (Fig. 2a) is constructed from cloud cover fractions at model sigma levels by applying the random overlapping method. Although some other method, for example, the random-maximum overlapping, might produce more realistic total cloudiness (Geleyn and Hollingsworth 1979, Tian and Curry

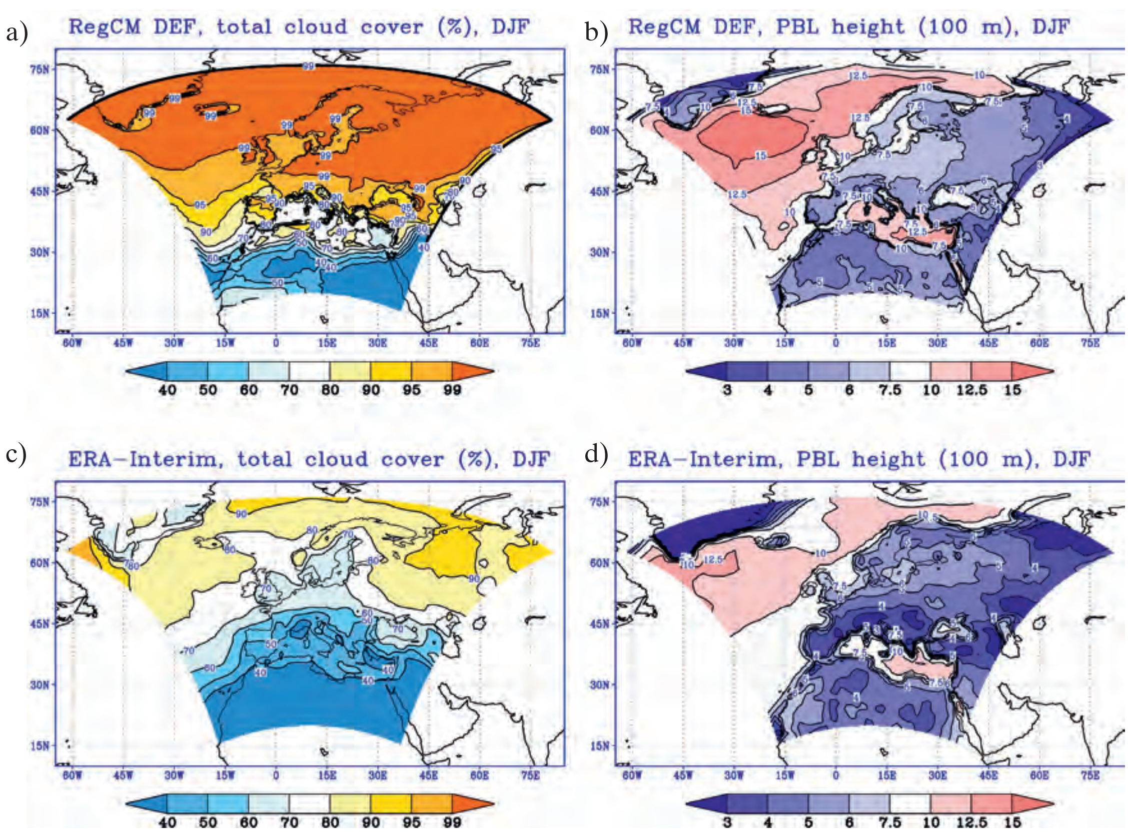

Figure 2: a) Total cloud cover and, b) the PBL height in RegCM4, c) total cloud cover and d) the PBL height in ERA-Interim.

Slika 2: a) Ukupna naoblaka i b) visina graničnog sloja u RegCM4, c) ukupna naoblaka i d) visina graničnog sloja u ERA-Interim.

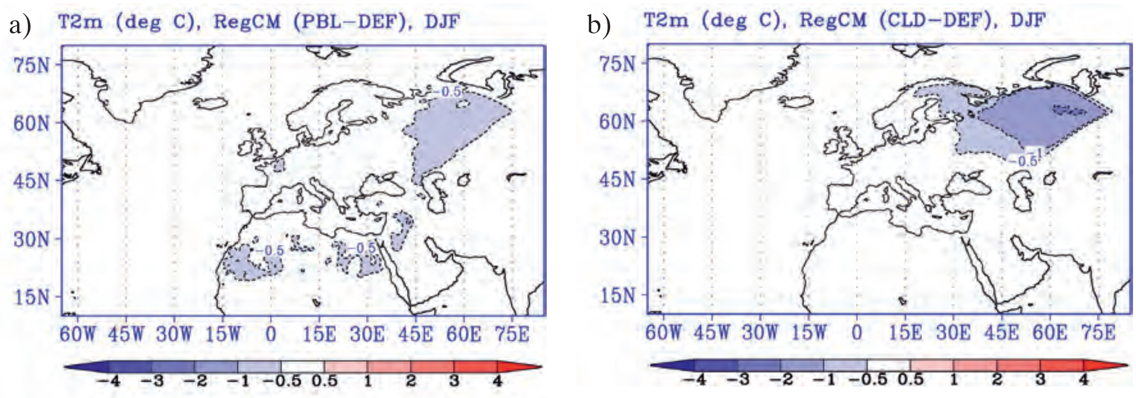

Figure 3: T2m bias in simulations with a) reduced minimum turbulent mixing in PBL (the PBL experiment) and b) reduced low level cloud cover fraction (the CLD experiment).

Slika 3: Pogreška T2m u simulacijama sa a) smanjenim minimalnim turbulentnim miješanjem u graničnom sloju (PBL eksperiment) i b) smanjenim udjelom naoblake u niskim slojevima (CLD eksperiment).

1989), in this way both the model-constructed and post-processed cloudiness are made consistent. In Fig. 2a, high values of total cloudiness in DEF, from 90% to 100% are seen over the northern Europe. This, in general, will reduce incoming solar radiation due to increased cloud albedo but also increase downward cloud longwave emission. Although the total cloud cover simulated by RegCM4 is increased up to 15% when compared with ERA-Interim (Fig. 2c), it is similar in terms of spatial distribution with the spatial corelation coefficient 0.87. However, this comparison must be taken with caution since clouds are computed differently in these two datasets.

The second hypothesis assumes that errors in reproducing certain PBL features in RegCM4 might adversely influence T2m. The current PBL scheme in RegCM4 describes vertical mixing as a function of the PBL height, its dependence of the height above surface and surface layer characteristics. In unstable conditions, there is an additional term that takes into account fluxes induced by convective eddies. From Fig. 2b and 2d it can be seen that, in both RegCM4 and ERA-Interim, the PBL top is higher over sea than over land. The differences between the two datasets over land can reach 300 m and this is roughly within uncertainty intervals determined from an analysis of soundings by different diagnostic methods (Seidel et al. 2010). Generally, there is a tendency of the PBL height in RegCM4 to be slightly higher than in ERA-Interim.

The impact of reduction of low-level cloudiness and reduction of vertical mixing on T2m is shown separately in Fig. 3. It is encouraging that the improvements in sense of reduced warm bias, consistent with both hypotheses, are located exactly in the region with largest positive bias shown in Fig. 1b. Although a better estimate of the impacts of changes in model physics would be obtained from an ensemble of simulations (e.g. O'Brien et al. 2010), in our single model integration the identical sign of changes in each simulated winter (not shown) indicates that the implemented modifications work in desired direction. The PBL modification reduces the warm bias up to 1°C (Fig. 3a) and the cloud cover modification reduces the bias up to 3°C (Fig. 3b). Clearly, neither approach by itself is sufficient to completely remove the warm bias; nevertheless, they show a potential to reduce a part of the bias. It must be emphasised, however, that the modifications considered are not strictly separated, i.e. changes in the PBL height can influence humidity and temperature profiles and hence cloud formation, while changes in cloud cover can influence surface radiation balance, the development of the turbulent mixing and consequently the PBL height. Small variations in modifications, such as the value of minimum turbulent mixing in PBL or the threshold in specific humidity in CLD, do not have a particular effect on the results.

The FIN experiment includes both modifications in vertical mixing (PBL) and cloud frac-

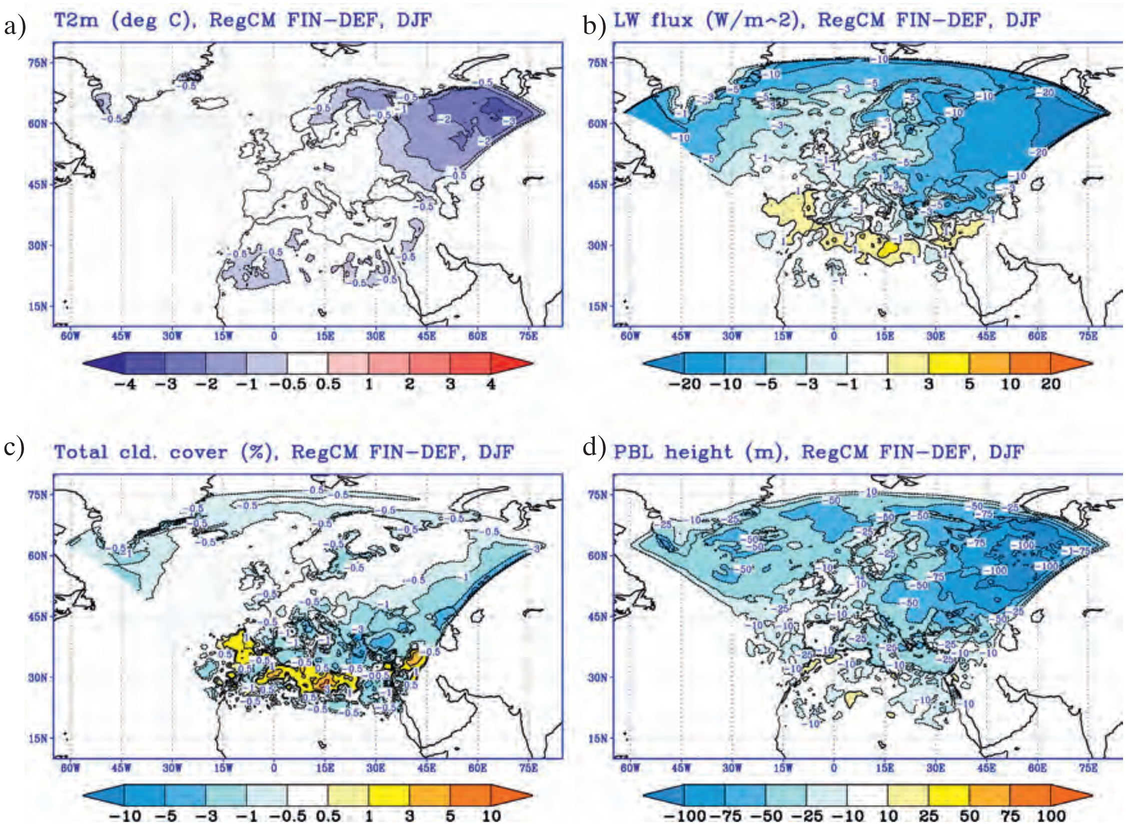

Figure 4: Differences between the simulation with default and final version of the model for a) T2m, b) downward surface longwave radiation flux, c) total cloud cover and d) the PBL height.

Slika 4: Razlike između simulacija sa osnovnom i konačnom verzijom modela za a) T2m, b) dolazni tok dugovalnog zračenja na površini, c) ukupnu naoblaku i d) visinu graničnog sloja.

tion (CLD). There is a reduction of up to 50% in temperature bias between FIN and DEF (Fig. 4a), and the reductions in downward surface longwave radiation (Fig. 4b) and the PBL height (Fig. 4d) are physically consistent with the improvements in T2m. The reduction of longwave radiation impacts surface radiative balance by reducing surface heating and the reduction of the PBL height can be interpreted, in a first approximation, as a mechanism to reduce heat capacity of the lowest atmospheric layer. Over the Sahara, the changes in total cloud cover (Fig. 4c) also coincide (the same sign) with the changes in downward surface longwave radiation flux, however, with no substantial changes in temperature. This is an area where the stable PBL can be formed during cold nights during entire year. However, the reduction of temperature bias over this area may require a different approach than described here.

The impact of modifications on T2m taken together is slightly different than the sum of separated contributions (not shown). Again, this can be partially explained by the fact that surface radiative balance and clouds are both functions of the temperature and humidity vertical profiles. On the other hand, because of internal variability of climate system, different circulations and weather formations might be caused by a slight difference in the model setup in the two simulations.

We next check if the modifications applied have an impact on the model simulation for other seasons. From the time series of area averages over 52°-57°E, 57°-62°N it is clear that the impact on T2m is pronounced only during DJF (Fig. 5a). A decrease of the PBL height can be also detected only for winter months (Fig. 5c) and the winter changes in Fig. 5c and Fig. 5a are mutually consistent.

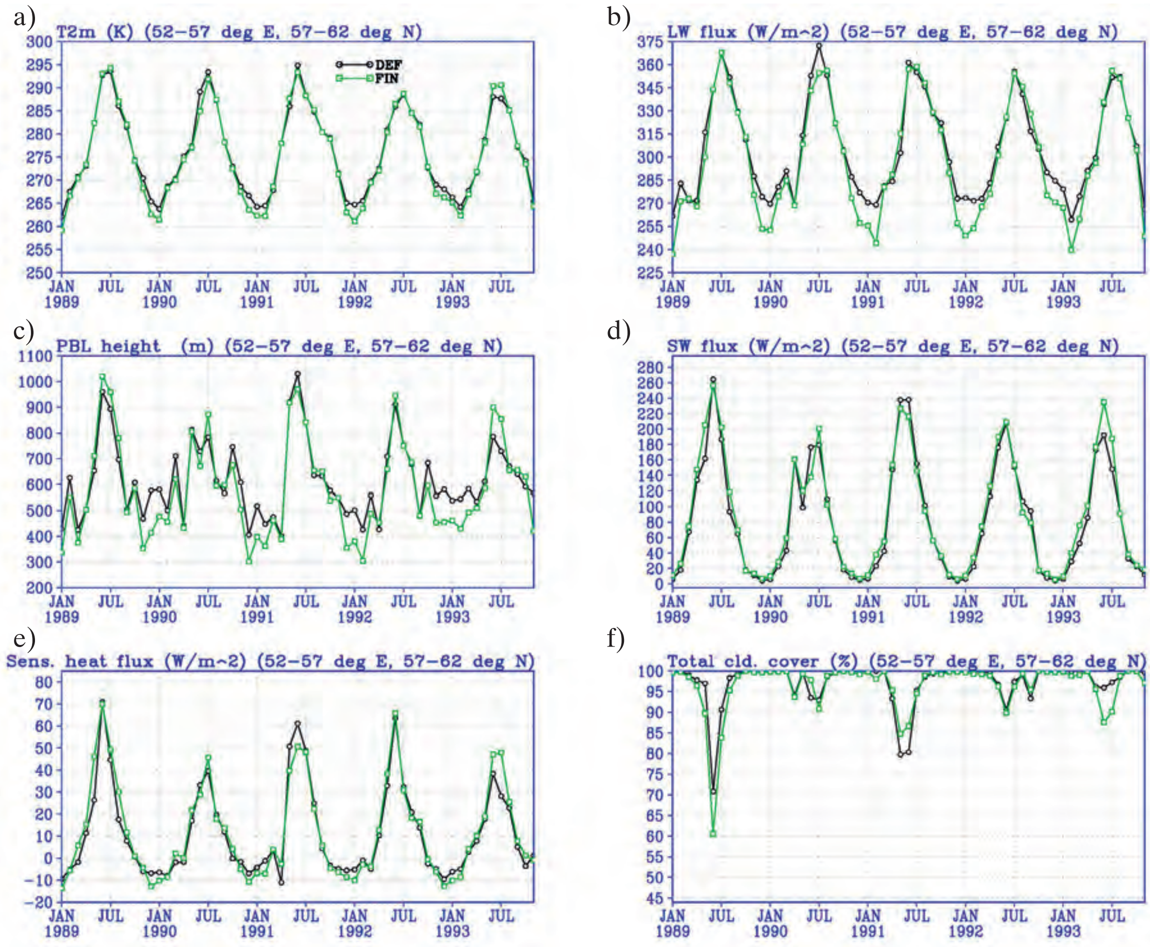

Figure 5: Timeseries of monthly and area averages for a) T2m, b) the PBL height, c) sensible heat flux, d) downward surface longwave radiation flux, e) downward surface shortwave radiation flux and f) total cloud cover. Simulation with the default model version (DEF) is in black with open circles and simulation with the final model version (FIN) is in green with open squares.

Slika 5: Vremenski nizovi mjesečnih srednjaka prostornih srednjaka za a) T2m, b) visinu graničnog sloja, c) tok senzibilne topline, d) dolazni tok dugovalnog zračenja na površini, e) dolazni tok kratkovalnog zračenja na površini i f) ukupnu naoblaku. Simulacija sa osnovnom verzijom modela (DEF) je označena crnom linijom i otvorenim krugovima a simulacija s konačnom verzijom modela (FIN) je označena sa zelenom linijom i otvorenim kvadratima.

Figure 5e clearly depicts that dynamic sensible heat flux in the cold part of the year is negative; this negative sign, after the following consideration, could be associated with stable boundary layers. The stability of PBL in RegCM4 is normally determined not by the sign of dynamic sensible heat flux but by the sign of kinematic virtual heat flux - if positive, PBL is unstable, and, if negative, it is stable. Although dynamic sensible heat flux can be converted into the kinematic form by a simple arithmetic, it contains no information about water vapour flux as kinematic virtual heat flux does (e.g. Stull 1988). It might be assumed, however, that water vapour flux is small in DJF (e.g. Przybylak 2003) and the sign of dynamic sensible heat flux could be therefore interpreted in similar way as the sign of kinematic virtual heat flux. Thus, as expected, the cold part of the year is associated with stable PBL. In our case, sensible heat flux in winter is reduced after the modifications were applied; however, this reduction in amplitude cannot substantially affect the occurrence of stable or unstable conditions - what matters here is the sign of the flux.

During the winter months, downward longwave radiation flux is reduced after the modifications were applied (Fig. 5b). Whereas this is consistent with the reduction in cloud cover fraction for layers below 750 hPa (not shown but cf. Fig. 6a), it is not so obvious in total cloud cover (Fig. 5f). Possible reductions in total cloud cover might have been masked by the random overlapping algorithm and its tendency to often overestimate total cloud cover amounts (e.g. Oreopoulos and Khairoutdinov 2003). Otherwise, total cloud cover in Fig. 5f shows larger variations in the warm part of the year, which could be attributed to internal variability rather than applied changes in the model physics. Figure 5d indicates that, in winter, there is little or no impact of the modifications on downward surface shortwave radiation flux. This is expected because the high-level cloud coverage in winter remains almost unchanged and hence there is no change in cloud albedo. An important feature in Fig. 5d is almost negligible shortwave radiation flux during the cold part of year (less than 40 Wm^{-2}) - this is the consequence of both large solar zenith angle in DJF and dominant high values of cloud coverage. This result points to relative importance of the longwave flux in the high-latitude regions.

In order to check the impact of the applied modifications to different parts of the domain, an analysis similar to that in Fig. 5 was made for the region in central Europe (20°-25°E, 45°-50°N). In winter, both the PBL height and downward longwave radiation flux in FIN are reduced when compared to DEF, but this reduction has no impact on T2m (not shown). For other parameters, changes in winter are much smaller than in high-latitudes or non-existent. Some discernible changes are seen in summer, but these are beyond the scope of this study.

To further investigate the role of clouds and some cloud-related variables, vertical profiles of seasonal multi-year averages over the same two regions as discussed above, were constructed. Among all cloud-related variables

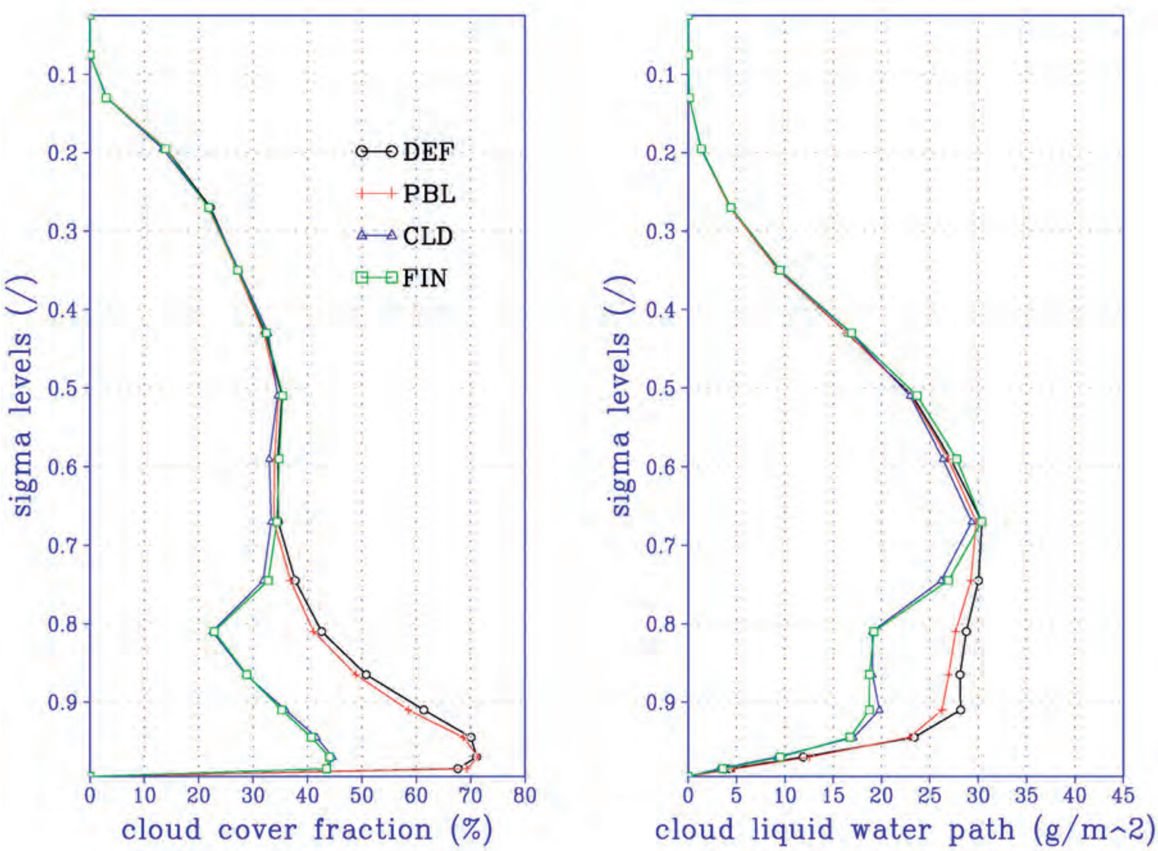

Figure 6: Vertical profiles of area averages of multi-year DJF mean of a) cloud cover fraction and b) cloud liquid water path. Profiles from all four experiments are shown. The area is 52°-57° E, 57°-62° N.

Slika 6: Vertikalni profili prostornih srednjaka višegodišnjih DJF srednjaka a) udjela naoblake i b) puta tekuće vode u oblacima. Prikazani su profili iz sva četiri ekperimenta. Područje je 52°-57° E, 57°-62° N.

considered in RegCM4, only cloud cover fraction and cloud liquid water are directly influenced by the CLD modifications defined in Vavrus and Waliser (2008). Figure 6a shows that the winter cloud cover fraction at high-latitudes is reduced at low levels in FIN and CLD relative to DEF and PBL. Cloud cover fraction at the first model level is by default set to zero in order to avoid the "fog-type" situations. However, regardless of this "forced" reduction, the overestimation of low-level cloudiness was detected already in the earlier versions of RegCM, indicating the need to better represent cloud and cloud-radiation processes in the model (Giorgi et al. 1998). The atmosphere at the middle and high model levels, directly above largest values of surface warm bias, is almost insensitive to the modifications in cloud cover. From Fig. 6 it can be seen that the reduction of cloud cover fraction and cloud liquid water content are primarily due to the modification in CLD, while the modification in PBL have detectable but smaller contribution (cf. Fig. 3).

The same result as in Fig. 6 is true for mid-latitudes as well, however, the reduction is less pronounced there than in the Subarctic region (not shown). The differences between FIN and DEF are seen in all seasons, but they are most pronounced in DJF. Cloud liquid water content is also reduced for the same levels, regions and seasons as for the cloud cover fraction.

4. SUMMARY AND CONCLUSIONS

The purpose of this study was to identify the existence of warm bias in RegCM4 model and to analyze the impact of modifications in cloud cover and PBL parameterization which contribute towards the reduction of such a bias. The modifications included steps to reduce downward longwave radiation flux and heat capacity in the lowest portion of the atmosphere. Eventually, the proposed modifications reduced warm bias up to 50% and can, therefore, be considered successful. The improvements are spatially confined and do not degrade the model results in other regions, seasons or vertical layers.

Further research on the subject would benefit from ability of an idealized framework (like, for example, the one-dimensional version of PBL and cloud microphysics parameterizations) which would help to test both hypotheses in more controllable setup. One limitation of the study is lack of observational data to directly validate cloud cover and PBL features; this would reduce possible unintentional error compensation that might appear when combining semi-dependent variables.

The tests similar to those described in this study were also carried out for some other regions of the world (central Asia and Siberia) where initial biases are much larger than over the north European domain (not shown), thus pointing to a serious modelling error. These regions also benefited from the applied modifications, i.e. the reduction of the warm bias has the same amplitude as in the European domain. This study was primarily focused on processes in the lower atmosphere and has not addressed the interaction with land-surface processes, such as, for example, the impact of snow cover on near-surface temperature. The high-latitude regions are very sensitive to the ongoing climate change and careful considerations of various modelling aspects are required in order to increase our confidence in climate simulations by RCMs.

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