CLM - The Climate Version of LM: Brief Description and Long-Term Applications

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1 Introduction

In 2001, LM was chosen as the basis for a new regional climate model called CLM. Although at this time numerous regional climate models already existed, there were at least two reasons for this decision. First, the non-hydrostatic formulation of the dynamical equations in LM without any scale assumptions made it eligible for use at horizontal grid resolutions of about 20 km and below, coming closer to the spatial scales requested by modelers of regional climate impacts. Secondly, the continuous development of LM at the DWD allows improvements in major LM versions to be adopted in the climate version ensuring that the central core is not a *frozen* one, but that of an up-to-date *living* forecast model. Meanwhile, we have succeeded in implementing extensions for long-term simulations into LM and in applying and evaluating the resulting CLM for multi-year climate reconstructions over Europe. Vice versa, these *climate mode* extensions will be made available in the forecast model as a new feature of LM 4.1.

In Section 2, we give a brief description of the major extensions implemented in LM 3.1 to obtain the CLM version 2.0. In Section 3, we present the CLM 2.0 setup for a 15-year simulation over Europe, give a short introduction into the developed validation strategy and assess the model's performance compared to analyses of the ECMWF (European Centre for Medium-Range Weather Forecasts), to observations and to results from simulations with other regional climate models under comparable conditions for reference. Finally, we summarize our findings, refer to the CLM as community model of the German regional climate modeling community and give an outlook on further model applications and recently started regional scenario constructions.

2 Brief Description of CLM Extensions

To enable LM for long-term simulations, the CLM community implemented several new features, some of them also of practical importance to the classical LM users. Therefore, all of them will be implemented into the upcoming LM version 4.1. In the CLM, we followed the general approach of adding switches to activate/deactivate the implemented extensions. In line with the general LM philosophy of modularity, all main climate extensions can be used by appropriate setting of the corresponding switches.

On climatological time scales, such model formulations as e.g. that describing the vegetation state of the soil cannot be assumed to be constant anymore as in the forecast mode. Therefore, we enabled the model to use not only initial values but also dynamic boundary data for `plcov`, `lai`, `rootdp`, `w_cl`, `t_cl` over land, for `t_s` and `qv_s` over sea, and for `vio3` and `hmo3` for the entire model area. To activate this feature, we implemented the logical switch lbdclim into the namelist group GRIBIN. Also, the switch lbdclim controls the output of variables with time range indicators 3 and 4 (mean and sum over the forecast time, respectively) which are reset after each output interval in order to avoid the calculation of output values as small differences of large numbers with limited numerical accuracy, as for instance for precipitation after 150 years model integration when estimating daily totals. There are intentions to extend the functionality of lbdclim to that of a *main climate mode switch*.

For climate change scenario simulations, the CO_2 concentration can be specified (constant at 330 ppm or an increase following the A1B and the B1 SRES scenario between 1950 and 2100, either for CO_2 only or composite CO_2).

We implemented a scale-selective type of relaxation, the spectral nudging. It can be activated and configured by setting parameters which we included in namelist group DYNCTL. In module organize_dynamics, a list is defined to indicate what set of boundary data are to be nudged. All subroutines performing the spectral nudging (initialization, spectral decomposition, nudging, spectral re-composition) are concentrated in module src_spectral_nudging.

For describing the thermal and hydrological processes in a deep soil, we use in the CLM Version 2.0 a modified DWD beta version of the multi-layer soil model. Different to this version, we apply this integration scheme in any case for both parts of the model (terra1_multlay and terra2_multlay). Having a thin first soil layer of about 1 cm thickness and a longer time step than 90 s, numerical oscillations of the surface temperature were encountered. To avoid such oscillations, a switch was implemented to allow restriction of the maximum change of t_so per time step to a user-defined value. Furthermore, the vertical soil moisture diffusion is restricted to layers above a certain depth, and a modified runoff computation is implemented. In namelist group PHYCTL, an additional parameter is introduced to externally control the lowermost depth for these hydrologically active soil layers. For the cases that there is snow cover, or there is no snow cover but t_snow is less than 0°C, the interception store water content is added to the snow store for consistency.

We also added parameters and routines that allow to write and read restart files and in this way to continue any model run.

Because of its portability, its self-describing character and because there is no risk of accuracy loss by data packing, we additionally implemented the NetCDF (Network Common Data Form) format for model input and output. In IOCTL, either NetCDF (following the CF, Climate and Forecast conventions) or GRIB1 can be selected individually for both the format of the initial and boundary data input files and that of the model output files. To handle NetCDF input and output, additional subroutines have been incorporated into the module io_utilities. Among them are all routines for opening/closing of NetCDF files, for reading and writing global definitions, variable-related attributes and data itself, but also for checking the input and output records.

Furthermore, several additional output variables were made available. In module data_fields, we defined equivalents for already existing model variables at 2m and 10m height indicated by the suffix _av with a time range indicator 3. They represent averages over the output interval (t_2m_av, td_2m_av, u_10m_av, v_10m_av) for use in namelist group GRIBOUT. Another 30 or so new variables have been defined for model output based on user demand. In addition to the cases already implemented in LM, the parameter ytunit in GRIBOUT is used to indicate a further 4-element date format (ytunit='d') including the month number in the file name convention (resulting date string: {yyyy}{mm}{dd}{hh}) set in subroutine make_fn.

In addition, further technical extensions are implemented. For example, in RUNCTL, the use

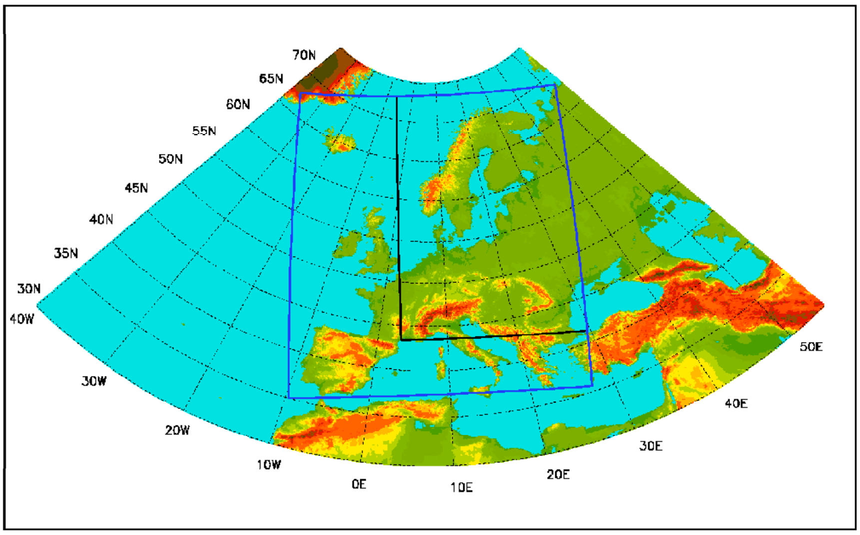

Figure 1: Extended BALTEX model region (blue borderlines) for ERA15-driven long-term runs over Europe. The original BALTEX model region is indicated by the black rectangle.

of a Gregorian or a climatological year can be specified.

3 Long-Term Climate Reconstruction over Europe

In a first long-term application, we used the CLM to reconstruct the climatic conditions over Europe for a 15-year period. For this purpose, we generated initial and lateral boundary conditions from ECMWF re-analysis data (ERA15). We set up the model for the so-called extended BALTEX region (Baltic Sea Experiment, `http://w3.gkss.de/baltex/`). The original and the extended BALTEX region which covers Europe almost completely are shown in Fig. 1.

We configured the multi-layer soil model with 10 layers and a total depth of ∼15 m. We used the climatological 2 m temperature as the lower boundary condition for the thermal part, which is in good agreement e.g. with observations at the station Potsdam. Initial soil moisture is set to 75% of the soil type depending pore volume in each grid box for all hydrological active layers. Initial and boundary data are generated for the entire ERA15 period 1979-1993. We used a horizontal resolution of 1/6 deg. (lat/lon) and 20 vertical levels in the pressure-based hybrid η-system. The north pole of the geographical grid is located at $\lambda = 170.0°$W and $\varphi = 32.5°$N. In this configuration, the lower left corner of the model area in rotated coordinates is located at $\lambda_r = 17.005°$W and $\varphi_r = 19.996°$S for mass grid points. We used 193×217 grid points which leads to the rotated coordinates for the upper right corner of $\lambda_r = 14.995°$E and $\varphi_r = 16.004°$N. We used a time step of 90 s. Boundary data are provided every 6 hours and relaxed using the Davies (1976) relaxation technique. The model output is stored with the temporal resolution of 6 h, too.

We elaborated a general verification strategy (Böhm et al., 2004) to assess the performance of a regional climate model using uni- and multivariate methods. Here, we concentrate on the model's ability to reproduce the regional climate exemplarily by evaluating the signed difference (bias) between the CLM results and suitable reference data for the three near-surface variables mean sea level pressure (MSLP), 2 m temperature and precipitation. Additionally,

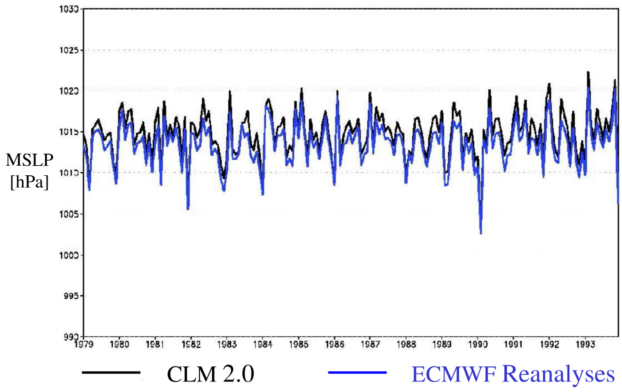

Figure 2: Area average of monthly mean MSLP 1979-1993.

we analyzed the accuracy of two temperature-related extremes – the number of summer days and the number of frost days – in the model results. For reference, we used ERA15 data, gridded observations that are compiled by the Climate Unit of the University of East Anglia (New, Hulme, Jones, 2000) and an observational data set of the German Weather Service. To compare the quality of the CLM results with those of other regional climate models that have been applied using the same forcing data, we supplied them to the QUIRCS project (Quantification of Uncertainties In Regional Climate and climate change Simulations, `http://www.tu-cottbus.de/meteo/Quircs/home.html`).

We analyzed the simulated mean sea level pressure as a representative of a rather large-scale climate variable. Fig. 2 shows that the CLM (black line) reproduces the ERA15 reference data (blue line) almost perfectly on average for the entire model area. Furthermore, there are no indications of a noticeable initial bias due to any cold start problem. The temporal mean of the area averaged MSLP generated by the CLM is, however, about 0.8 hPa higher.

In climate impact research, the 2 m temperature is a key variable. In Fig. 3, the 15-year annual mean is shown for both the CLM (left panel) and the CRU high-resolution gridded reference data set for most of the European land areas (right panel). Please note that the coordinate axes are labeled in rotated geographical coordinates in this figure and also in Figs. 4, 6, 7 and 9.

As a general result, there is evidence for the model's ability to reproduce the spatial patterns as represented in the gridded reference data set. This is especially true for mountainous regions.

However, the model underestimated the 2 m temperatures nearly everywhere over land. This becomes more clearly visible in Fig. 4 where the 15-year mean bias is shown. Whereas over Northern and North-Western Europe the smallest differences can be observed, the largest systematic deviations occur over land areas of high elevation in the south.

The already mentioned QUIRCS project addresses the question of how the identified model inaccuracies of different regional climate models compare. A final report is in preparation, and status reports are available on the above-mentioned home page. Here, we use the QUIRCS model results as an anonymous reference for the CLM. Figure 5 shows the mean annual cycle of the 2 m temperature for CLM 2.0, three other models and two reference data sets, averaged over the CRU region as indicated by the dark green-colored area in Fig. 9. Again, CLM 2.0 (black line) provides colder temperatures than both ERA (red line) and

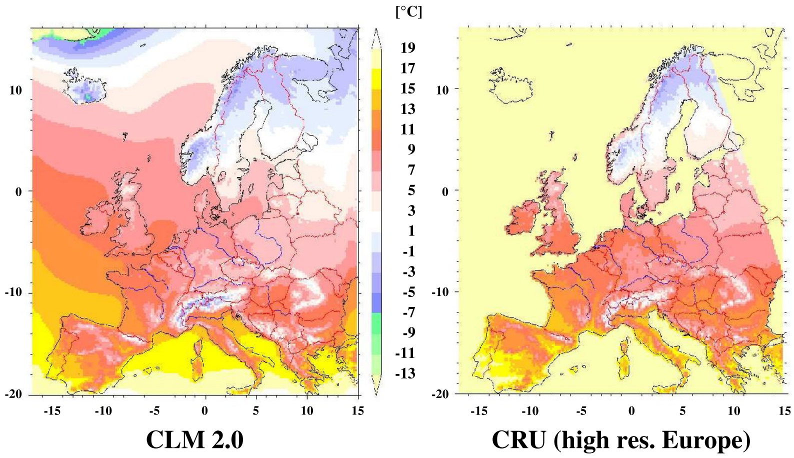

Figure 3: 15-year mean of annual mean 2 m temperature 1979-1993.

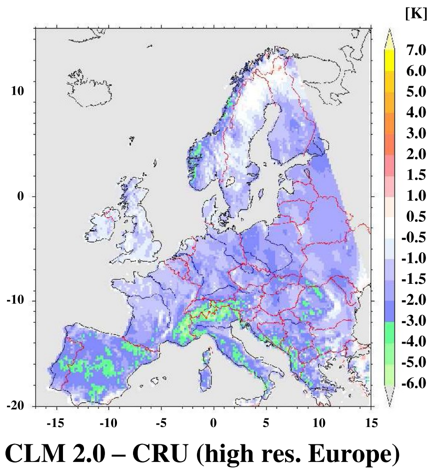

Figure 4: 15-year mean bias CLM – CRU of annual mean 2 m temperature 1979-1993 over the region as shown in Fig. 3, right panel.

CRU reference data (grey line) during summer. During winter, the bias compared to ERA is smaller than the difference between both reference data sets. Two of the three other models in Fig. 5 simulate too high temperatures especially during summer and early autumn with higher absolute differences for July and August than for the CLM. During winter, the other models range between the two reference data sets.

On average over the year, the CLM underestimates the 2 m near-surface temperatures by about 1.75K/ 0.67K compared to the CRU/ERA data set. Bearing in mind the different sign of the bias for two of the three other models during summer and winter compared to the CRU data set, this result indicates that the CLM provides an accuracy which is comparable to that of the other models participating in QUIRCS. The identified CLM bias lies within the range of about 2 K which is a typical order of magnitude for present-day regional climate models

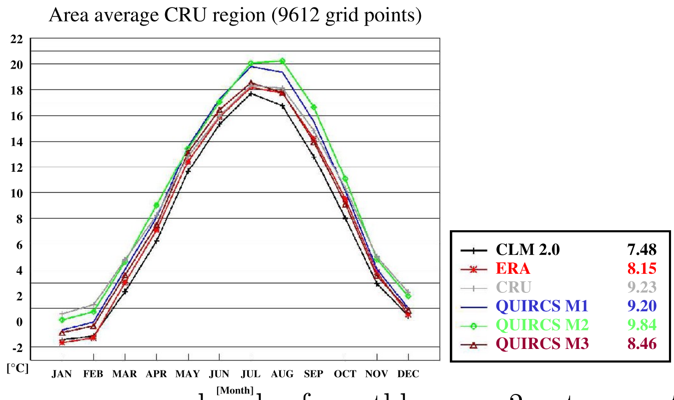

Figure 5: 15-year mean annual cycle of monthly mean 2 m temperature 1979-1993. CLM 2.0, ERA and CRU: as explained in the text. QUIRCS M1, M2 and M3: three other models participating in the QUIRCS project.

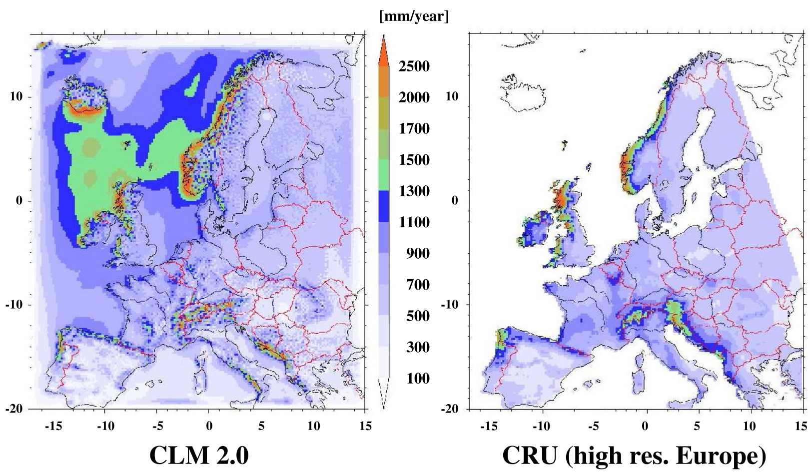

Figure 6: 15-year mean of annual total precipitation 1979-1993.

as concluded in the PRUDENCE project (Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects, see Christensen, 2005). Possible sources of this model inaccuracy are discussed after assessing the model's ability to reproduce the temperature-related extremes at the end of this section.

Although precipitation is a much more inhomogeneous quantity, Fig. 6 shows in the left panel that the model is also able to reproduce the major features of the spatial patterns in the CRU reference data set (right panel), especially over Great Britain, Scandinavia, the Alps, the northern Balkan region and northern Portugal.

Different to the 2 m temperature, however, there is no homogeneous picture for the sign of the bias. In Fig. 7 it becomes clearly visible that a gradient exists from the north - where the model simulates too much precipitation - to the south, which is reproduced as being too dry by the model, with the exception of some mountainous and coastal areas there. From subsequent investigations, there are indications that this north-south gradient of the bias at least partially may be caused by a too restrictive soil temperature change damping (not reported here).

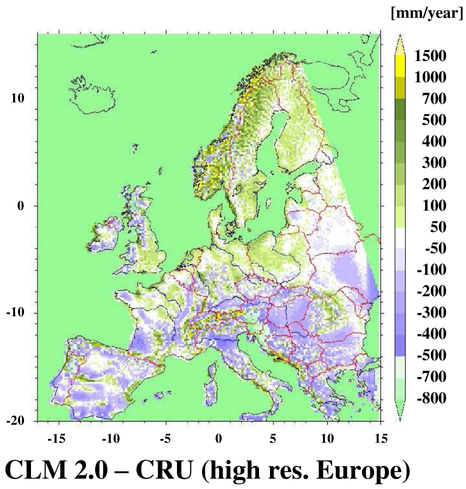

Figure 7: 15-year mean bias CLM-CRU of annual total precipitation 1979-1993 over the region as shown in Fig. 6, right panel.

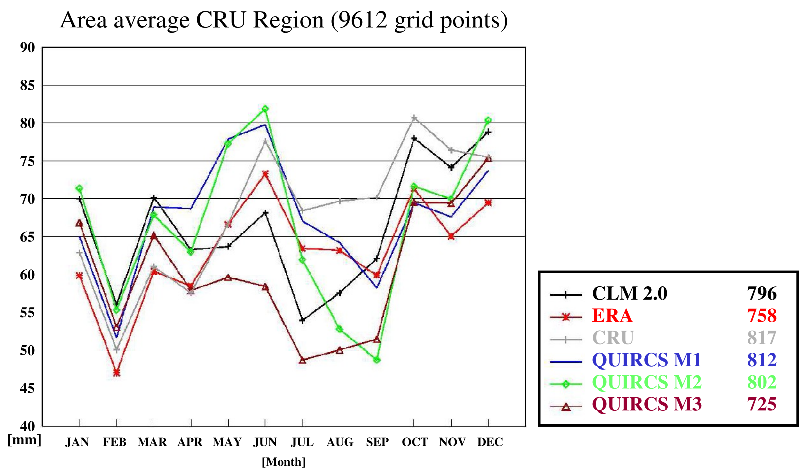

Figure 8: 15-year mean annual cycle of monthly total precipitation 1979-1993. Meaning of acronyms as in Fig. 5.

We also analyzed the relation of CLM's precipitation bias to that of other models participating in the QUIRCS project. In general, the variety between the models is much wider than in the case of the 2 m temperature, as it is obvious in Fig. 8, where the annual cycle of precipitation, averaged over the CRU region is shown in CLM 2.0 results, in the results of three other models involved in QUIRCS, and also in the ERA15 and CRU reference data.

The CLM provides some evidence of an overestimation of precipitation during winter and early spring, whereas the model underestimates precipitation during the rest of the year. Compared to the other models, the CLM is again within their characteristic range of uncertainty. We estimated an annual relative bias of -3% and of +5% in relation to the CRU and ERA data set, respectively. These values represent the lower boundary of errors as estimated for typical present-day regional climate models in the PRUDENCE project (Christensen, 2005).

In Kotlarski et al. (2005), the model intercomparison results for 2 m temperature and precip-

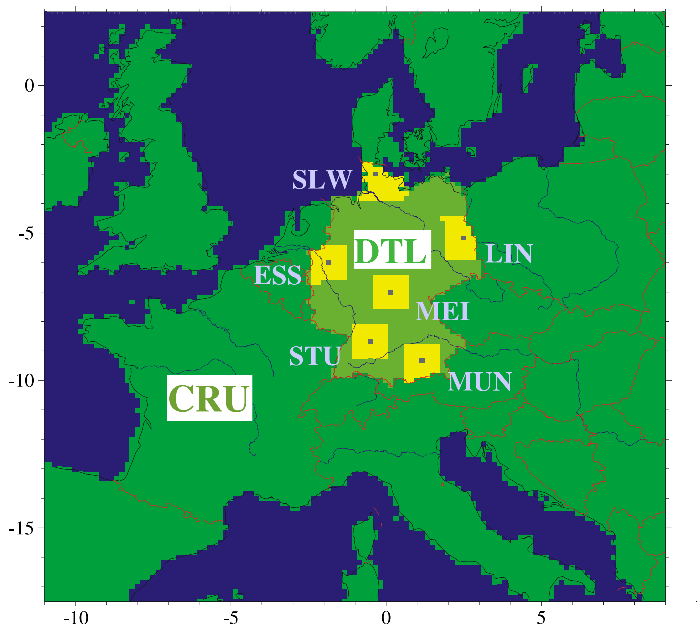

Figure 9: Regions for model verification. CRU: Land area covered commonly by all models and the CRU high-resolution reference data set. DTL: Germany SLW (Schleswig), ESS (Essen), LIN (Lindenberg), MEI (Meiningen), STU (Stuttgart) and MUN (Muenchen): smaller diagnosis regions centered around the indicated cities.

itation are described in more detail, for Germany in particular, and reveal the applicability of the CLM for regional climate simulations at spatial resolution of about 18 km (Kotlarski et al., 2005).

For climate impact research, extremes become more and more important. Especially during transitions from one climate to another one, there are indications that extremes occur more often and their amplitude intensifies.

Therefore, we assessed CLM's ability to reproduce temperature and precipitation extremes. Here, we concentrate on two examples of temperature-related extremes over Germany as a whole and over several smaller regions with specific climatic conditions ranging from north to south as shown in Fig. 9. We calculated the bias between the results of the CLM and a set of station observations from the German Weather Service, and compared it to the bias as estimated within the QUIRCS project for the same three models as listed in Fig. 5.

In Fig. 10, the number of summer days, i.e. the number of days with a daily maximum temperature equal to or higher than 25°C, is shown for the individual models and sub regions. The green circles representing the bias CLM results - DWD data set illustrate that the CLM performs well for DTL. The results for the smaller sub regions, however, give evidence that this outcome is based on averaging effects for larger differences with a slightly increasing tendency from north to south. Compared to other models, the CLM results are located at the lower limit of the range of errors.

The picture is different for the number of frost days with minimum temperatures below 0°C. Figure 11 shows that the CLM overestimates these extremes over almost all investigated regions and ranges at the upper error limit as estimated within the QUIRCS project.

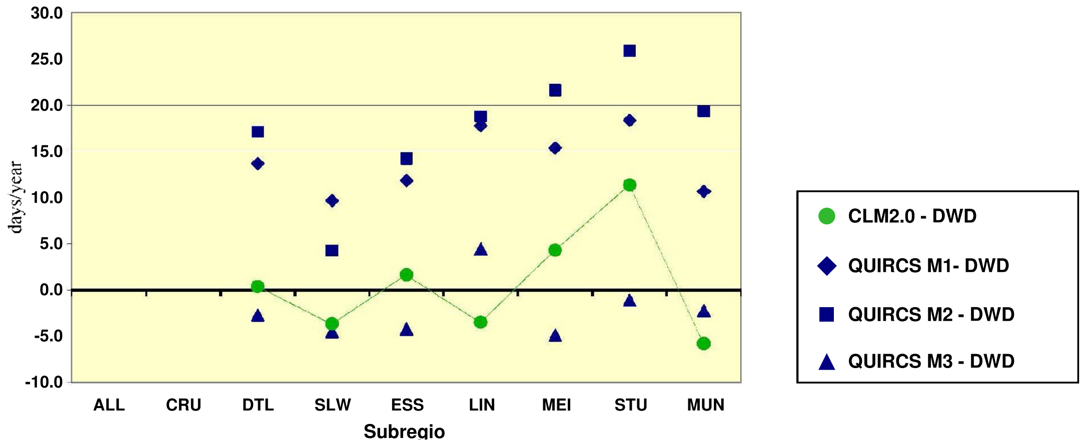

Figure 10: 15-year mean bias for the number of summer days per year for the CLM (green circles) and the models as indicated in Fig. 5, averaged for the regions as shown in Fig. 9.

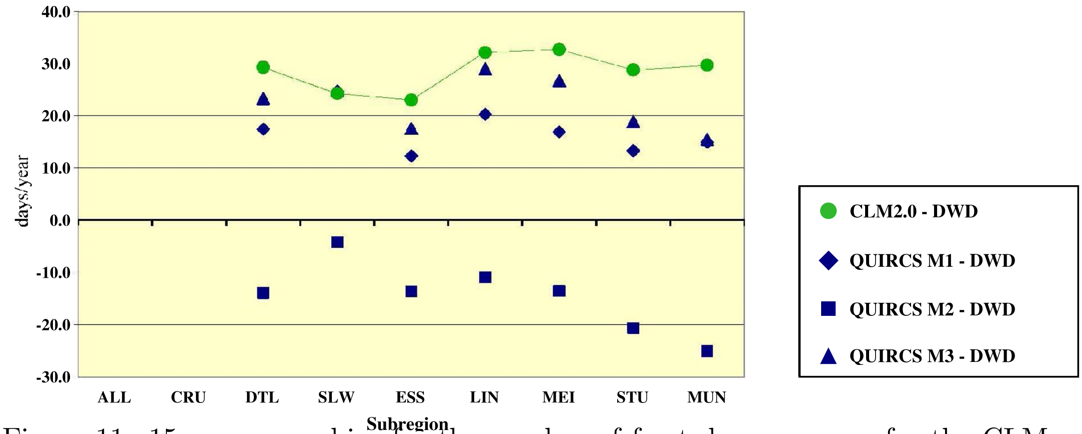

Figure 11: 15-year mean bias for the number of frost days per year for the CLM (green circles) and the models as indicated in Fig. 5, averaged for the regions as shown in Fig. 9.

This result gives evidence that the negative 2 m temperature bias in Fig. 5 compared to the CRU data set over Europe during winter exists also in relation to DWD observations over Germany and that ERA data seem to be too cold.

There are indications that the cold bias of the CLM may be caused at least partially by the strong damping of the soil temperature change of 2K/h in the multi-layer soil model which becomes important during summer. Subsequent analyses (not reported here) revealed, that this configuration leads to an imbalance of the surface energy budget. Therefore, we changed this limit to a less restrictive value (actually 20K/h in CLM 2.4).

Consistently with it, further analysis of the bowen ratio showed the sensible heat flux to be overestimated and the latent heat flux to be underestimated during spring, summer and autumn. This problem may, in turn, be also linked to the representation of root depths in the soil sub model in the CLM. Recent sensitivity experiments with a modified description of root depths provide changes in the bowen ratio in the right direction and are, therefore, encouraging. So far, however, no long-term simulations considering these changes are completed which would allow complementing the verification and intercomparison as described here.

4 Summary and Outlook

We extended the LM version 3.1 to the CLM version 2.0 to enable the model to perform long-term simulations. Most of the extensions are controlled by independent switches ensuring compatibility with the underlying forecast version. The most important new features of the CLM are: the usability of additional dynamic boundary conditions for vegetation and ozone parameter, for the surface temperature and humidity over sea and for the deep-soil lower boundaries, the possibility to specify changing CO_2 concentrations following two climate change scenarios, the spectral nudging technique, the use of an altered type of a modified DWD beta version of the multi-layer soil model, the possibility to continue a simulation from a user-defined model restart point, NetCDF following the CF conventions as an additional input and/or output format, the output of mean and total values for different output intervals instead for the entire forecast period only, the availability of additional output variables and the choice between a Gregorian or a climatological calendar year. They will be made available to the LM users in LM 4.1.

We presented results of the 15-year evaluation run of CLM 2.0 over Europe using ERA15 data as initial and boundary data. We evaluated atmospheric and near-surface variables for this simulation experiment. In this contribution, we discussed the model performance exemplarily for near-surface climate elements representing both mean conditions and extremes. The model simulated too cold temperatures, overestimated the precipitation over Northern Europe, and underestimated it over Southern Europe. The diagnosed bias for both 2 m temperature and precipitation is comparable to that of other present-day regional climate models and could at least partially be attributed to a too restrictive damping of the soil temperature changes in the applied multi-layer soil model, which could be overcome, however, in forthcoming model versions. Therefore, we conclude that CLM 2.0 is appropriate for simulating regional climates. Due to its non-hydrostatic formulation, we see the potential of the model, however, at finer horizontal grid sizes of about 10 km and below.

Based on the evaluation of the CLM results described here and on additional diagnostics of atmospheric variables, the Scientific Advisory Board (WLA – Wissenschaftlicher Lenkungsausschuss) of the German Climate Computing Centre (DKRZ) declared CLM as community model for the German regional climate modeling community. Linked to this declaration, a Community Agreement has been formulated and all interested scientists are invited to join the community and to contribute to the development of the CLM. Until now, scientists from 11 institutions have joined it. In addition, CLM has been selected to perform so-called consortial runs to generate small ensembles of transient regional climate scenarios for the period 1960-2100 at 0.165 deg. lon/lat resolution according to the SRES scenarios A1B and B1 (IPCC, 2001) forced by the global coupled model ECHAM5/MPIOM.

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