COSMO-CLM

Impact of land use and soil data specifications on COSMO-CLM simulations in the CORDEX-MED area

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Abstract

The impact of the ECOCLIMAP land use and the Harmonized World Soil Database (HWSD) data on simulations with the Consortium for Small-scale Modeling model in CLimate Mode (CCLM) regional climate model is investigated. ECOCLIMAP has information about vegetation characteristics as monthly data for 215 climatic units. With the HWSD implementation in CCLM, the spatial resolution of the soil data has been increased to 30 arc seconds and has an improved texture definition and handling in the soil model TERRA_ML. Simulations in the MED-CORDEX modeling domain over the period 1986–2000 reveal that differences of up to 1.8 K in the area monthly mean temperature as well as of up to 21 % in the area monthly mean precipitation can be attributed to the differences in the soil data time-invariant boundary input. Differences related to changes in land use are with 0.4 K and 5 % moderate. Differences resulting from the soil data and its processing in CCLM indicate that regional climate model simulations might benefit from further improvements in this area.

Keywords: RCM, lower boundary conditions, MED-CORDEX

Thermal and hydraulic soil properties, land use with associated vegetation and surface characteristics, and topography are basic time-invariant lower boundary input data in any regional climate model (RCM). Recent experiments with the regional climate model COSMO (Consortium for Small-scale Modeling) in CLimate Mode (CCLM) presented by Anders and Rockel (2009) and Guillod et al. (2013), who investigated the impact of soil map specifications on climate simulations, indicate that climate models would benefit from improved quality of the time-invariant lower boundary data and from addressing unresolved issues in land-surface modeling.

The general importance of the basic time-invariant lower boundary input in RCM simulations has been addressed by several publications (Mölders, 2005; Ge et al., 2007; Teuling et al., 2009; Hong et al., 2009; Sertel et al., 2010), revealing the need for both improved basic input as well as the evaluation of the impact the data may have on RCM simulations. In CCLM experiments with basic time invariant data from CCLM and Weather Research and Forecasting Model (WRF) in the Mediterranean area Smiatek (2014), attributed variations of up to 1.1 K in the area mean monthly mean temperature and up to 17 % of the observed value in area mean monthly precipitation to differences in the land use, topography, and soil data. By varying the data

sources of the leaf area index (LAI), vegetation cover, soil data, and related parameters in a CCLM modeling domain covering Europe, Block (2007) has shown changes in annual mean values on the order of 0.25 K for the 2-m temperature. In simulations over Europe, Guillod et al. (2013) linked differences of 2 K in the mean temperature and 20 % in the mean precipitation to changes in the soil texture model input.

The scientific aim of the present article is the systematic evaluation of the choice of the data on land use and soil characteristics on the current CCLM simulations. The investigated sources of land use data are the GLC2000 (Global Land Cover Map for the year 2000) (GLC2000, 2002), which is standard in CCLM, and the experimental ECOCLIMAP (Masson et al., 2003; Champeaux et al., 2005). ECOCLIMAP has been available in CCLM since 2008 but so far it has never been systematically evaluated. The investigated sources of data soil characteristics are the Digital Soil Map of the World (DSMW), which is standard in CCLM, and the HWSD (Harmonized World Soil Database) Nachtergaele et al. (2012). In order to facilitate the application of HWSD in CCLM, the TERRA_ML soil model applied in CCLM has been accordingly extended.

The present paper is structured as follows: Section 1 describes in broad terms the considered land use and soil data, the extension of the TERRA_ML soil model, and the design of the experiment. The results are presented and discussed in Section 2, and conclusions are drawn in Section 3.

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1 Material and methods

1.1 Land use data input

The Global Land Cover Map for the year 2000 (GLC2000) compiled at the Joint Research Centre of the European Commission (JRC) has a spatial resolution of 1 km × 1 km. The basic data input to this joint effort of several research teams was the daily SPOT4 Vegetation sensor data (Bartholomé and Belward, 2005). CCLM provides an appropriate lookup table, linking the applied 23 land use categories with vegetation characteristics such as the Leaf Area Index (LAI), roughness length (z_0), root depth, and others. GLC2000 is the standard land use data applied in CCLM.

ECOCLIMAP (Masson et al., 2003; Champeaux et al., 2005) is an optional data set implemented in CCLM. It is a global database of land surface parameters at a spatial resolution of 1 km. The data is based on land use data from Geosphere-Biosphere Programme Data and Information System (IGBP/DIS), CORINE (coordination of information on the environment) programme, the Pan-European Land Cover Monitoring project (Mucher et al., 2000), and the climate map of Koeppe and De Long (1958). Within ECOCLIMAP, 215 different ecosystem units are distinguished, of which about 140 units occur within the Mediterranean realization of the WCRP Coordinated Regional Downscaling Experiment (MED-CORDEX). For these units, a set of surface parameters, mostly in monthly resolution, is provided. The parameters range from LAI, roughness length (z_0), root depth, emissivity, and albedo to various vegetation fractions. The ECOCLIMAP implementation in CCLM has been discussed in detail by Smiatek et al. (2008). Recently, Faroux et al. (2013) presented a new version, ECOCLIMAP-II, which applies the GLC2000 (CORINE land cover, CLC (2004)) and GLC2000 land use data, the leaf area index (LAI) from MODIS, and the vegetation index from the SPOT satellites. This database is available for Europe only and is not yet implemented in CCLM. Table 1 summarizes the applied land use data.

1.2 Soil data input

The Digitized Soil Map of the world (DSMW) (FAO, 2002) is a global data set created by the FAO Land and Water Development Division at a scale of 1:5,000,000 and is applied as the standard soil characteristics data in CCLM. DSMW provides textural information on the proportions of clay (fraction less than 2 microns), silt (2–50 microns) and sand (50–200 microns) in the upper 30 cm of the dominant soil type. In the CCLM implementation, this information is converted to five textural classes: coarse, coarse to medium, medium, medium to fine, and fine, and extended with additional categories: ice, lithosols, and histosols. Each textural class is then linked with 13 different hydraulic and thermal soil parameters. The accuracy in the small number of textural classes is rather low.

With the completion of a comprehensive update of the DSMW, the new Harmonized World Soil Database (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012; Nachtergaele et al., 2012) contains over 16000 different soil mapping units with a grid resolution of about 1 km (30 arc sec), and distinguishes physical and chemical characteristics for topsoil (0–30 cm) and subsoil (30–100 cm) conditions. In addition to the higher grid resolution, in its provision of the fractions of sand, silt and clay, the HWSD database increases substantially the accuracy of the soil texture information. In the present implementation in the TERRA_ML, only the information from the top soil layer together with the regression relationships for physical soil properties have been applied. Implementation of the texture change within the considered soil column is planned for the future. Table 1 summarizes the applied soil data.

1.3 HWSD Implementation in TERRA_ML

The five textural classes of the FAO which are used to retrieve five soil types with one dominant type in a grid box of the COSMO model do not appropriately reflect the variability in the soil properties. This becomes important in high-resolution limited area model simulations. Therefore, in this study, the linking of soil-texture based soil types with the corresponding hydraulic properties of the soil is replaced by regression relationships (Wösten et al., 1999; Hollis et al., 2012). The basic soil properties, available from the HWSD but also from high resolution regional soil inventories, i.e., the fractions of sand f_{sand}, silt f_{silt}, clay f_{clay}, and organic matter f_{OM}; and the bulk density ρ_b, are used to retrieve the hydraulic properties. Only for special soil states or when the basic soil properties are unknown are the prescribed values applied. For the latter, certain values of ferralic arenosols are assumed: i.e., $f_{sand} = 91.7\%$, $f_{silt} = 3.3\%$, $f_{clay} = 5.1\%$, $f_{OM} = 0.27\%$, $\rho_b = 1.5\,g\,cm^{-3}$, which are also used for shifting sand (dunes). For histosol (peat), the parameters of organic soil according to Balsamo et al. (2009) are employed. Soil hydrological processes are not considered for soil states associated with continental ice (glaciers), rock (lithosols), alkali flats, or soil sealing (urban areas). Details of the HWSD implementation in TERRA_ML are provided in the supplementary material.

1.4 Experimental design

1.4.1 Modeling domain

The investigated modeling domain was chosen according to the setup of the WCRP Coordinated Regional Downscaling Experiment (CORDEX) in its Mediterranean realization (MED-CORDEX). The size of the computational domain was 114×79 grid cells at a horizontal resolution of $0.44°$ (about 50 km) in a rotated grid. Fig. 1 illustrates the domain extent in an unrotated map projection.

Table 1: Sources of the land use and soil data.

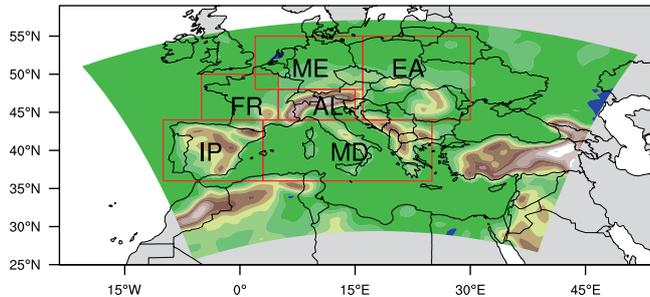| Item	Acronym	dx	Source
Soil texture	DSMW	5 arc min	FAO, FAO (2002)
	HWSD	30 arc sec	FAO/IIASA, NACHTERGAELE et al. (2012)
Land use	GLC2000	30 arc sec	JRC Ispra, GLC2000 (2002)
	ECOCLIMAP	30 arc sec	MASSON et al. (2003)

Figure 1: Model domain and evaluation regions.

Table 2: Performed simulations.

Acronym	Land Use	Soil data	Initialization
GLC_FAO	GLC2000	DSMW	01.01.1986
GLC_FAO2	GLC2000	DSMW	02.01.1986
GLC_FAO3	GLC2000	DSMW	03.01.1986
ECO_FAO	ECOCLIMAP	DSMW	01.01.1986
ECO_FAO2	ECOCLIMAP	DSMW	02.01.1986
ECO_FAO3	ECOCLIMAP	DSMW	03.01.1986
GLC_HWSD	GLC2000	HWSD	01.01.1986
GLC_HWSD2	GLC2000	HWSD	02.01.1986
GLC_HWSD3	GLC2000	HWSD	03.01.1986
ECO_HWSD	ECOCLIMAP	HWSD	01.01.1986

Table 3: CCLM configuration in runs with boundary data from ERA40 reanalysis.

Parameter	Value
Domain size	114×79
Grid spacing	$0.44\,°$
Number of layers	32
Number of soil layers	9
Time step	240s
Time range	1986–2000
LBC update frequency	6h
Dynamics	LF
Physics	TKE

The $0.44\,°$ model runs were carried out with ERA40 reanalysis data over a period of 15 years, 1986–2000, where the first five years are considered as spin up time and all evaluations were limited to the ten year period from 1991 to 2000. The soil moisture was initialized with soil moisture data from the coarse grid of the driving model relative to pore volume. Application of ERA boundary data makes the results of the present study comparable with the standard CCLM evaluation presented by KEULER et al. (2012). Table 2 depicts the matrix of the performed simulations. In order to access the internal model variability (IVAR) the simulations GLC_FAO, ECO_FAO and GLC_HWSD were repeated twice with model initialization time shifted by one day to the 2nd and 3rd of January 1986. In the literature, different measures have been used for the assessment of the internal variability (ALEXANDRU et al., 2007; LUCAS-PICHER et al., 2008; BRAUN et al., 2012). The present article employs the maximum spread between the single realizations.

All tests were performed applying the CCLM version 4.9_29 with an extended TERRA_ML model. In TERRA_ML with HWSD, individual soil texture categories no longer exist. Therefore, parameterization schemes where specific parameters depend on the prescribed soil texture category (all simulations with the DSMW/FAO soil data) were replaced by previously implemented schemes. For this reason, the soil heat conductivity scheme according to PETERS-LIDARD et al. (1998) and JOHANSEN (1975) was used in this study and for the bare-soil evaporation, an approach following NOILHAN and PLANTON (1989) was used. Table 3 shows the details of the CCLM configuration. The main level depths of the applied soil layers are 0.01, 0.035, 0.08, 0.17, 0.35, 0.71, 1.43, 2.87, 5.75, 11.51 m.

The evaluation of the CCLM runs was accomplished in the evaluational MED-CORDEX domain in 98×63 size and in six investigation areas, namely the Iberian Peninsula (IP), the Mediterranean (MD), the Greater Alpine Area (AL), Mid-Europe (ME), France (FR), and Eastern Europe (EA) (Fig. 1), all against the European daily high-resolution gridded data set E-OBS Version 8.0 (HAYLOCK et al., 2008; VAN DEN BESSELAAR et al., 2011). All statistics consider land points only. Because all simulations use the same elevation data, no height correction was applied in comparison with the E-OBS reference.

The use of a CORDEX model domain and the standard evaluation areas applied in the PRUDENCE (CHRISTENSEN and CHRISTENSEN, 2007) or ENSEMBLES (BOBERG et al., 2010) regional experiments allow considering the results of the present study in the context of various recent RCM evaluations, e.g., JACOB et al. (2007); KJELLSTRÖM et al. (2010); KEULER et al. (2012); JACOB et al. (2014).
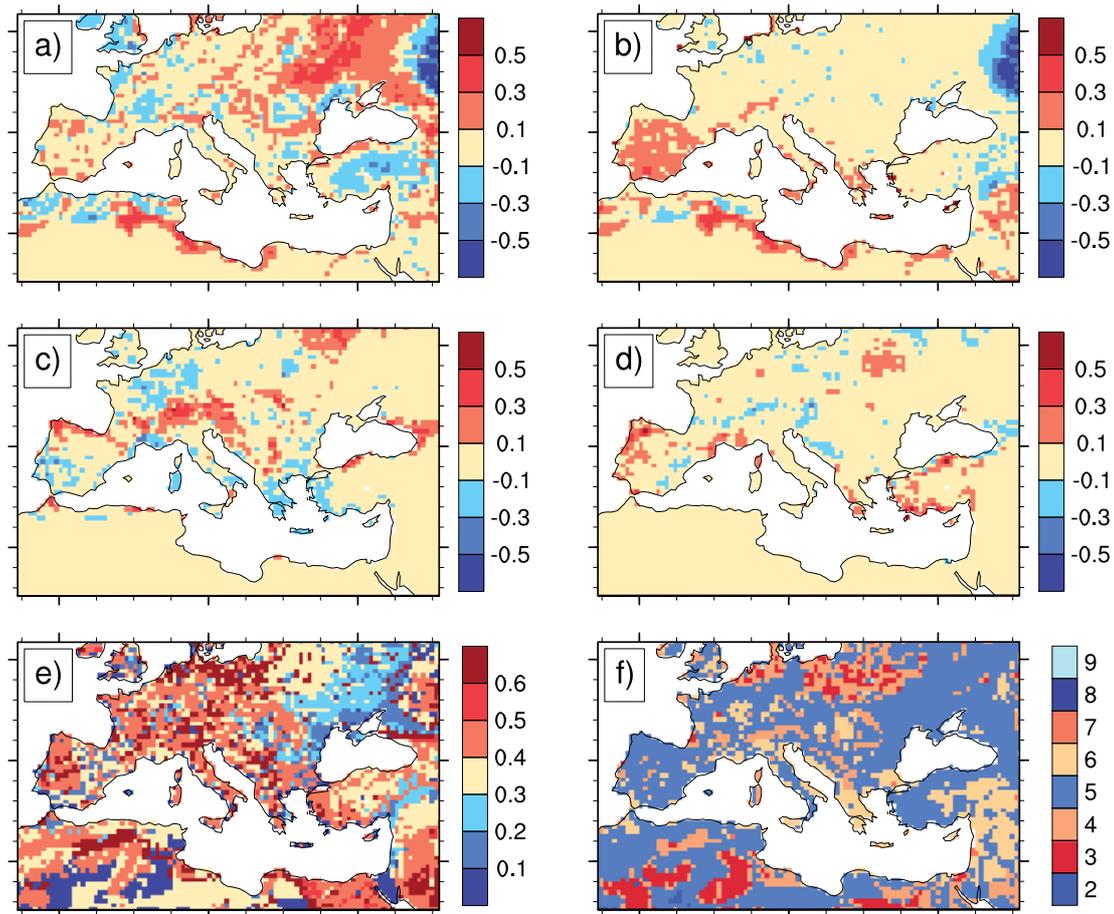
Figure 2: Land use and soil data applied in the present experiment. Differences between GLC2000 and ECOCLIMAP a) minimum plant cover fraction, b) maximum plant cover fraction, c) proportion of deciduous forest, d) proportion of coniferous forests. Soil data applied in the present study: e) fraction of Sand in the HWSD data and f) soil texture categories in DSMW/FAO database.

Fig. 2 displays the differences between GLC2000 and ECOCLIMAP for minimum and maximum plant cover as well as the proportions of deciduous and coniferous forest. The largest differences occur in the Iberian Peninsula, Mid-Europe, the Alpine area, and in the north-east of the domain. The implementation of the DSMW/FAO in TERRA_ML employs soil texture categories. Because the HWSD implementation uses the percentages of sand, silt, and clay, a direct comparison of the data sets is difficult. However, as shown in Fig. 2e, the HWSD data are much more detailed than the soil texture categories derived from DSMW/FAO and illustrated in Fig. 2f.

Table 4 shows the area average monthly mean leaf area index (LAI) of the ECOCLIMAP data and the minimum/maximum value applied with GLC2000 in the investigated areas. The maximum values vary by up to 0.8 and the minimum values by up to 0.4. The largest differences can be found in the areas IP and AL.

1.4.2 Applied statistics

The applied statistics are in line with typical RCM evaluations studies, e.g., Jacob et al. (2007); Samuels et al. (2011); Keuler et al. (2012), and include climatological monthly area mean of 2-m temperature (T_2M), diurnal temperature range (DTR), precipitation amount (RR), mean sunshine duration (DURSUN), sea level pressure (MSLP), and volumetric soil water content (VWC).

Further investigated statistics include seasonal mean values of the minimum 2-m temperature (TN), maximum 2-m temperature (TX), latent heat flux (λH), sensible heat flux (SH), evaporative fraction (EF = λH/(λH + SH)), long wave upward radiation (LW$_{out}$), and surface evaporation (E).

2 Results

2.1 Internal variability

In order to trigger internal model variability (IVAR), the reference simulation with standard land use and soil input (GLC_FAO) was repeated twice with a time offset of one day in the starting date each time. Fig. 3 illustrates the internal variability for mean 2-m temperature (T_2M), mean precipitation (RR), mean sunshine duration (DURSUN), and mean sea level pressure (PMSL) in the winter (DJF) and summer (JJA) seasons. All investigated variables show a clear annual cycle with maximum values of up to 0.4 K, 0.4 mm/d, 16 min, and 8 Pa

Table 4: Area mean leaf area index (LAI) values associated with the ECOCLIMAP and GLC2000 data sets in the Iberian Peninsula (IP), Mediterranean (MD), Greater Alpine Area (AL), Mid-Europe (ME), France (FR) and Eastern Europe (EA). Minimum and maximum values of ECOCLIMAP LAI are in bold face.

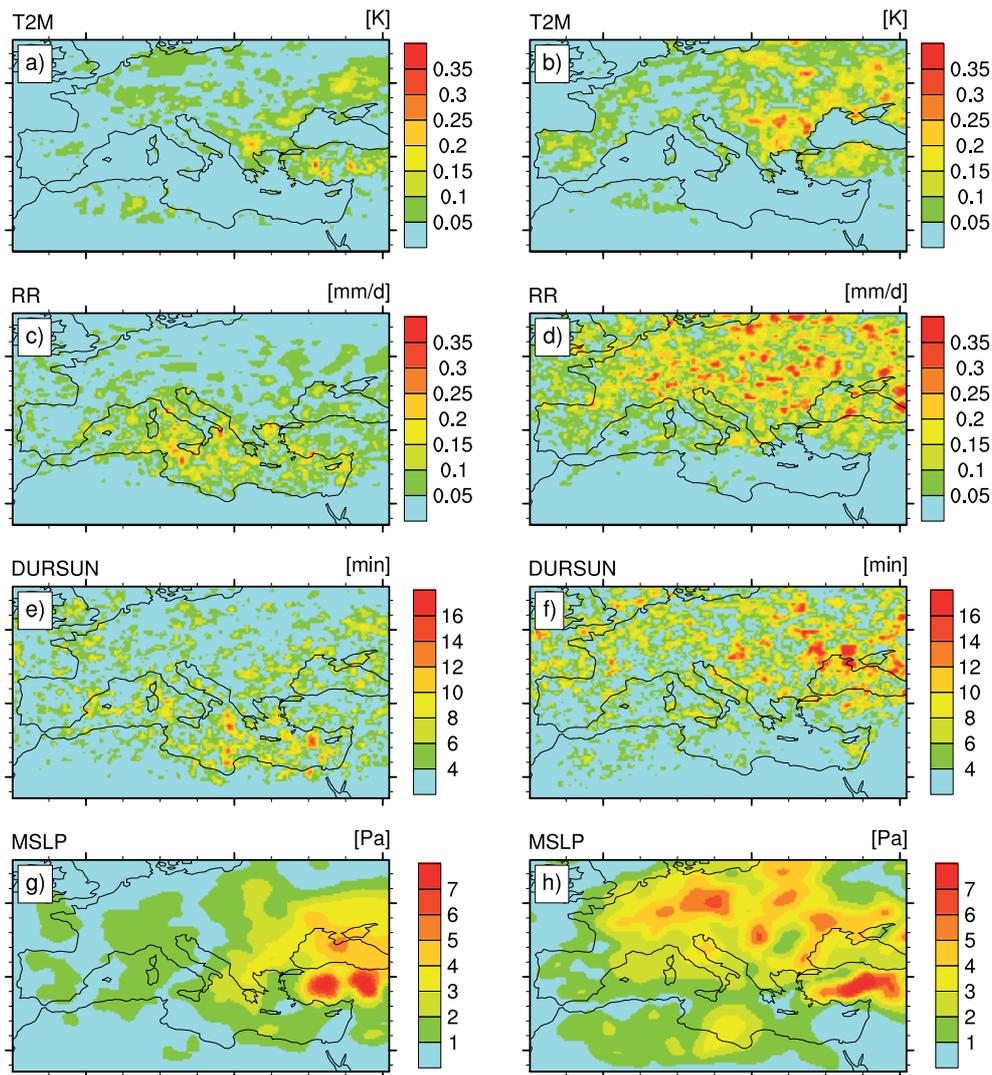| UG | ECOCLIMAP monthly values | | | | | | | | | | | | GLC2000 | |
	01	02	03	04	05	06	07	08	09	10	11	12	Minimum	Maximum
IP	**1.0**	1.2	1.5	1.6	**1.7**	1.6	1.6	1.5	1.4	1.3	1.1	1.1	0.6	2.5
MD	**0.7**	0.9	1.1	1.2	**1.4**	1.3	1.2	1.2	1.1	1.0	0.8	**0.7**	0.3	1.3
AL	**1.2**	1.6	2.0	2.3	3.0	**3.2**	**3.2**	3.1	2.9	2.5	1.8	1.3	0.9	4.0
ME	**1.0**	1.4	1.7	2.2	3.2	**3.3**	3.0	2.8	2.6	2.3	1.7	1.1	0.7	3.1
FR	**1.0**	1.4	1.9	2.4	**2.8**	2.7	2.5	2.4	2.3	2.0	1.3	1.1	0.6	2.5
EA	**0.9**	1.2	1.6	2.1	3.2	**3.5**	3.4	3.2	2.9	2.3	1.6	1.0	0.8	3.8

Figure 3: Internal variability: a) mean DJF T_2M, b) mean JJA T_2M, c) mean DJF RR, d) mean JJA RR, e) mean DJF DURSUN, f) mean JJA DURSUN, g) mean DJF PMSL, h) mean JJA PMSL.

in the summer season. This is in agreement with previous IVAR studies. As found, e.g., by LUCAS-PICHER et al. (2008), the internal model variability reaches its maximum in regions close to the outflow boundary. In their experiments with Community System Model Version 3 (CCSM3), DESER et al. (2012) estimated the internal variability to account for at least one-half of the inter-model spread in projected climate trends.

2.2 Model bias

Fig. 4 shows the differences between the area mean monthly mean 2-m temperature (T_2M) and the observational E-OBS reference in the six investigation areas. The biases are in range of the biases found by KEULER et al. (2012), who investigated the influence of various model configurations on CCLM re-
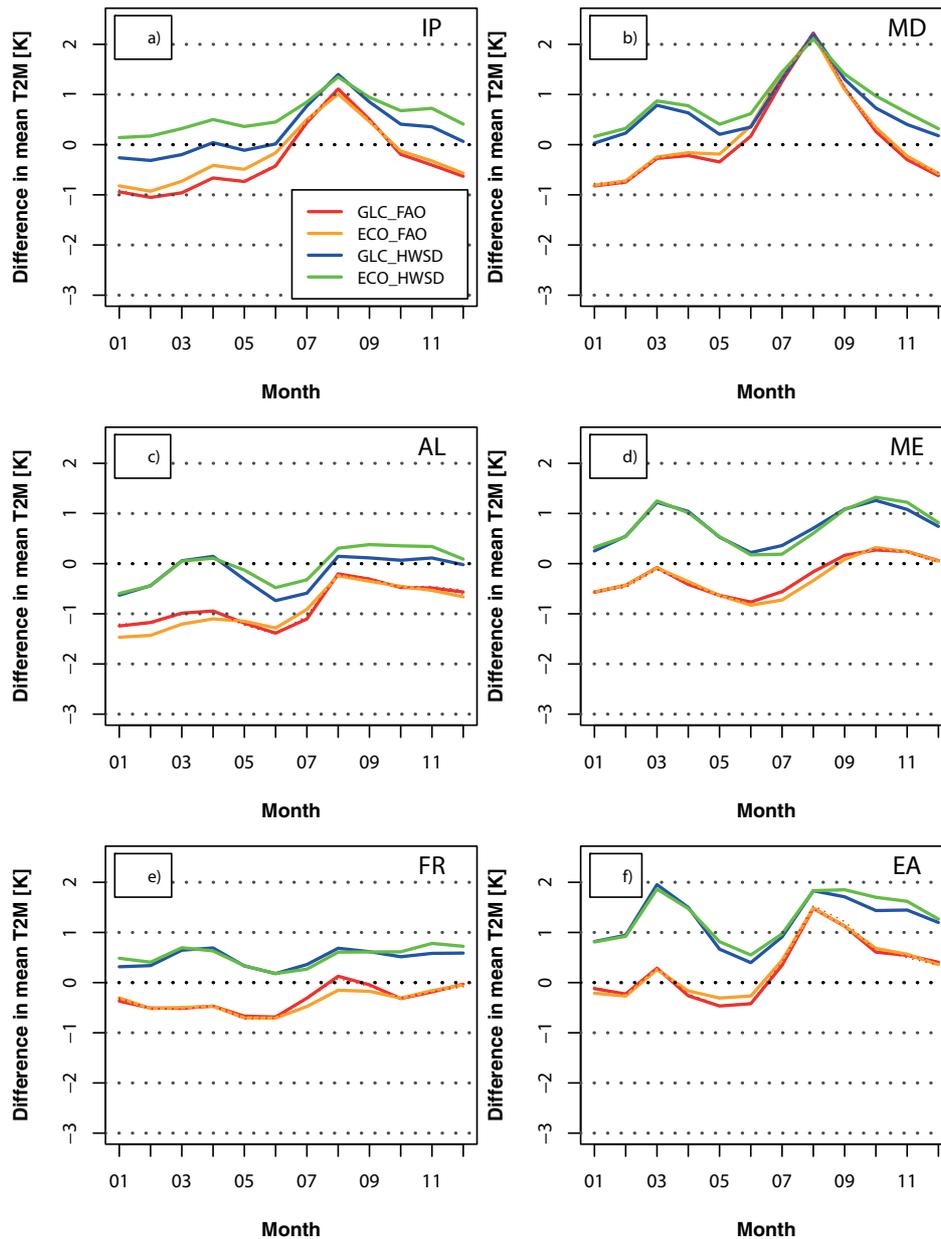
Figure 4: Difference between the simulated area monthly mean temperature (T_2M) and the gridded E-OBS observational reference for the period 1991–2000. a) Investigation area IP, b) investigation area MD, c) investigation area AL, d) investigation area ME, e) investigation area FR and f) investigation area EA.

sults in experiments driven with ERA40 reanalysis data. A model configuration is a set of parameters defining the model grid, physics, dynamics, and numerics used in the simulation. Fig. 4 reveals only moderate differences between the model runs which differ in the applied land use and the associated vegetation parameters (GLC_FAO/ECO_FAO and GLC_HWSD/ ECO_HWSD). They reach a maximum value of 0.4 K in the monthly mean 2-m temperature, with highest values in the IP area.

Larger differences, up to 1.8 K, occur between the runs which differ in the employed soil characteristics data. With exception of the summer season, the simulations ECO_FAO and ECO_HWSD reveal smaller biases

in the southern investigation areas IP and MD compared to the GLC_FAO/ECO_FAO simulations. In the complex Alpine terrain (AL), this is the case throughout the year. In the investigation areas ME and FR, the biases of GLC_FAO/ECO_FAO and GLC_HWSD/ECO_HWSD are similar but with different signs. Only in EA are the biases found in simulations with the recently implemented HWSD soil data larger than the bias obtained with the DSMW(FAO) soil database.

The bias in simulated monthly area mean precipitation is in the range between −29 mm/month and 36 mm/month and in the majority of the months, below 20 mm/month (Fig. 5). This is in agreement with the CCLM evaluation of KEULER et al. (2012) and the
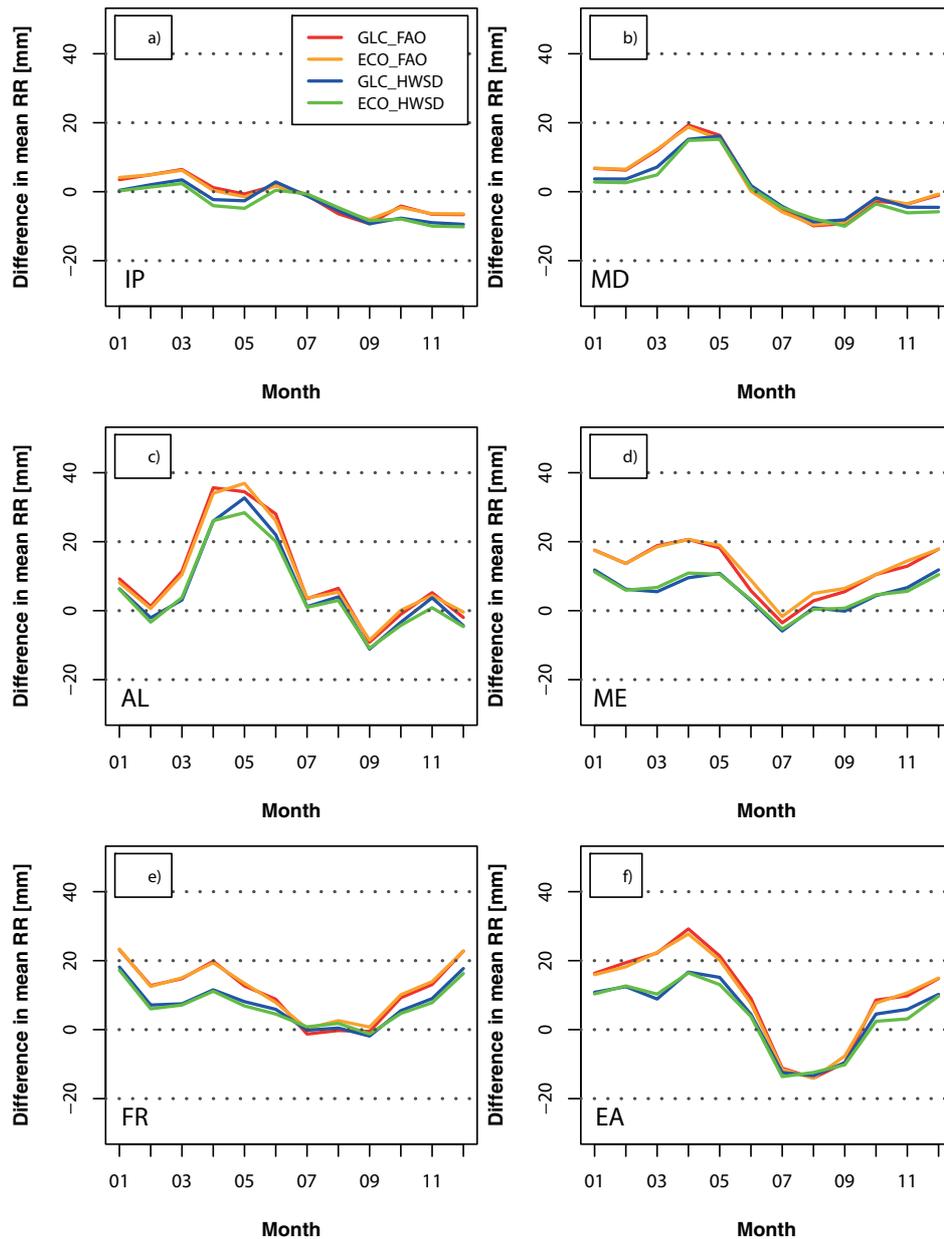
Figure 5: Difference between the simulated area monthly mean precipitation (RR) and the gridded E-OBS observational reference for the period 1991–2000. a) Investigation area IP, b) investigation area MD, c) investigation area AL, d) investigation area ME, e) investigation area FR and f) investigation area EA.

model evaluations PRUDENCE and ENSEMBLES. The differences between the single simulations reach in the EA area a maximum of about 0.4 mm/d which is about 21 %. Again, simulations driven with the replaced soil data and extensions in the TERRA_ML soil model seem to reduce the bias in almost all regions and months. The differences between the simulations and the observations are in part the result of a combination of model errors, reanalysis errors, and errors in the observations, but these errors cannot be analyzed by the present experiment. Therefore a general recommendation remains difficult. This is supported by Fig. 6, which illustrates the biases in the daily temperature range DTR. Here the simulation applying the HWSD soil data reveals larger

biases in all investigation areas. Those errors can be traced to a substantial overestimation of the monthly area mean minimum temperature in all investigation areas (not shown), which exceeds 2 K in the majority of the months and reaches 3 K in August. Changes in soil heat conductivity associated with the HWSD data might partially explain this. As the performance of those simulations concerning the monthly area mean maximum temperature is generally better, there is potential for further improvements in the soil model.

2.3   Differences between the model runs

In what follows, we concentrate on the differences caused by the use of the two different land use data
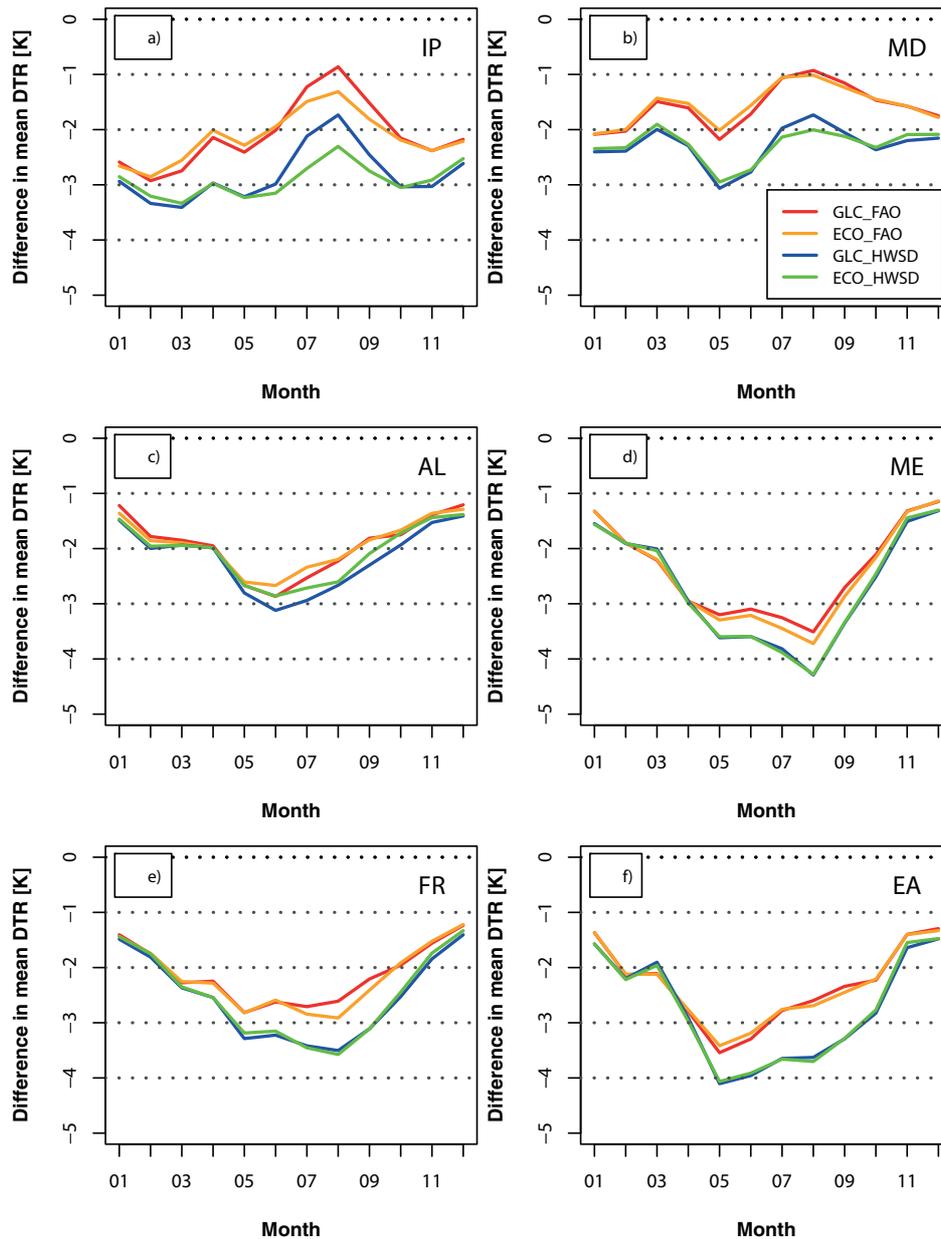
Figure 6: Difference between the simulated area mean monthly daily temperature range (DTR) and the gridded E-OBS observational reference for the period 1991–2000. a) Investigation area IP, b) investigation area MD, c) investigation area AL, d) investigation area ME, e) investigation area FR and f) investigation area EA.

sources, GLC2000 and ECOCLIMAP, together with each of the two different soil databases, DSMW/FAO and HWSD. Spatial maps depicting the differences between the simulations GLC_FAO and ECO_FAO as well as the differences between GLC_FAO and GLC_HWSD for the winter season (DJF) are shown in Fig. 7 (See Table 2 for explanations of these acronyms). Fig. 8 illustrates the differences found in the summer season (JJA). Large differences are found on the coast and some lakes between the GLC_FAO and ECO_FAO. They can be attributed to the differences in the land sea mask derived from the land use data. GLC2000 and ECOCLIMAP originate from different sources, thus small variations in the land sea mask may occur. Beside those single

grid cells, no larger differences are found. One exception is the Alpine region, where the 2-m temperature in the ECO_FAO is up to 0.5 K cooler. The differences in the mean precipitation reach ±0.3 mm/d and in the sunshine duration 15 min/d. The picture seen in the differences between the GLC_FAO and GLC_HWSD is entirely contrary. The GLC_HWSD run is, with a few exceptions, more than 1 K warmer over the entire domain. Also, it shows an up to 30 minutes longer sun shine duration and is in large areas up to 0.5 mm/d dryer. Only small differences of up to 0.9 hPa occur in the Balkans and Turkey in the mean sea level pressure (PMSL).

The patterns of differences between GLC_FAO and GLC_HWSD found in the summer season (JJA) are sim-
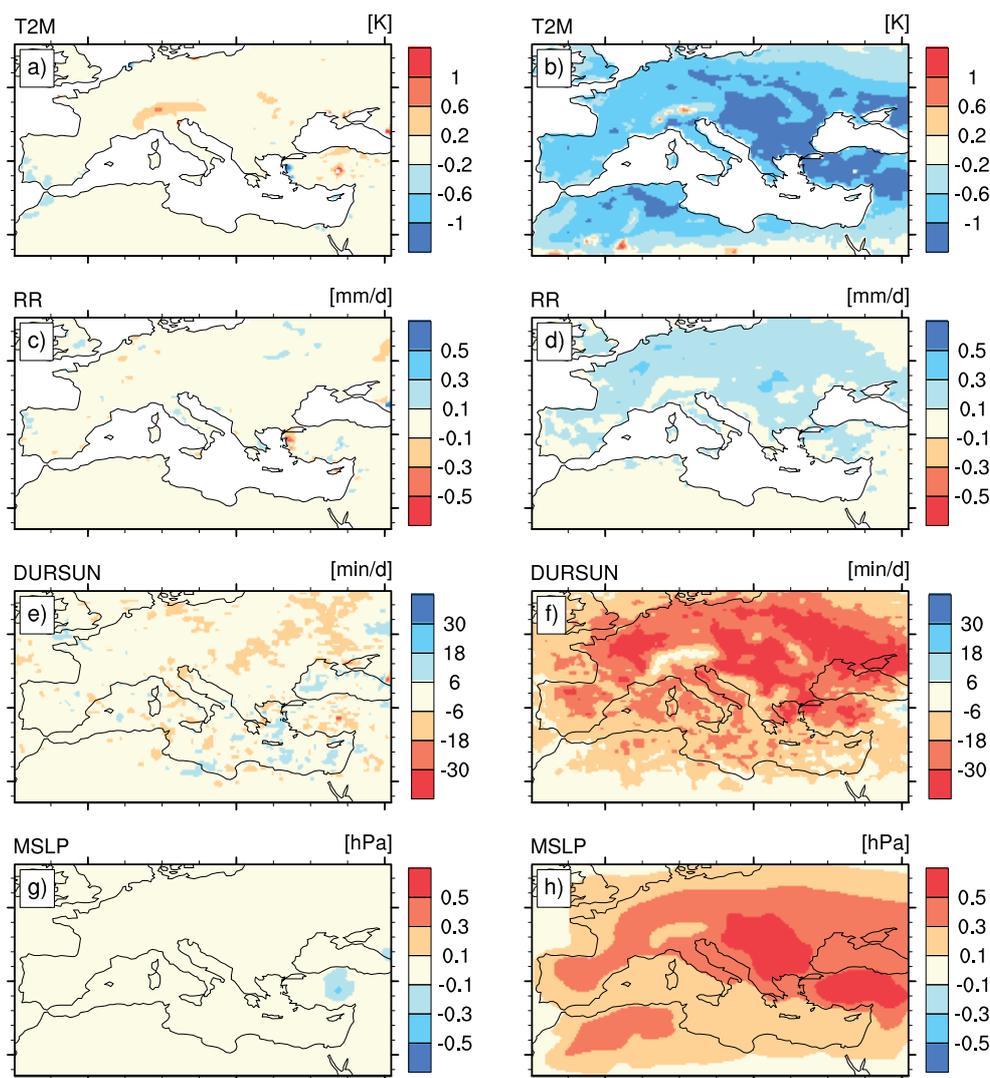
Figure 7: Differences between the model runs GLC_FAO and ECO_FAO (left column) and GLC_FAO and GLC_HWSD (right column) and the mean values for the winter season (DJF). a, b) T_2M c, d) RR e, f) DURSUN and g, h) PMSL.

ilar, however the mean differences are lower than for the winter season (DJF). Again, the GLC_HWSD is warmer and drier in large parts of the domain. The largest differences in all considered variables are found in Mid-Europe. On the other hand, the differences between the model runs GLC_FAO and ECO_FAO for the summer season are larger than for the winter.

In the present study, different data sources for the lower boundary soil characteristics cause larger differences in mean temperature and precipitations in the spring season, which disagrees with experiments with various data sources for soil characteristics by GUILLOD et al. (2013), who found the largest differences in the summer season. It is generally expected that surface and sub-surface processes have a larger impact on near-surface temperatures in the summer, when more radiative energy is available at the surface. While differences in the summer can be traced to vegetation influencing the partitioning of the available energy between sensible and latent heat, boundary layer temperature and mois-

ture (PITMAN, 2003), or surface albedo (FORSTER et al., 2007), already small variations in the temperature in the winter season could influence the soil moisture. On the other hand, it is difficult to disentangle the individual contributions from the changes in the soil database as well as the applied parameters, such as hydraulic conductivity, hydraulic diffusivity, thermal conductivity and bare soil evaporation.

Fig. 9 depicts the differences between the model runs of GLC_FAO and ECO_FAO, as well as between the simulations GLC_FAO and GLC_HWSD, for the sensible heat flux (SH), latent heat flux (λH), evaporative fraction (EF), and long wave upward radiation (LW$_{out}$) for the summer season (JJA). Land use changes cause only moderate changes in SH, λH, EF, and LW$_{out}$ in the summer season. In the winter (not shown), noticeable changes from that cause occur only in the southern part of the domain. Changes that can be related to the soil data are larger. Differences in SH and λH mostly compensate each other. Changes in SH and λH which can be
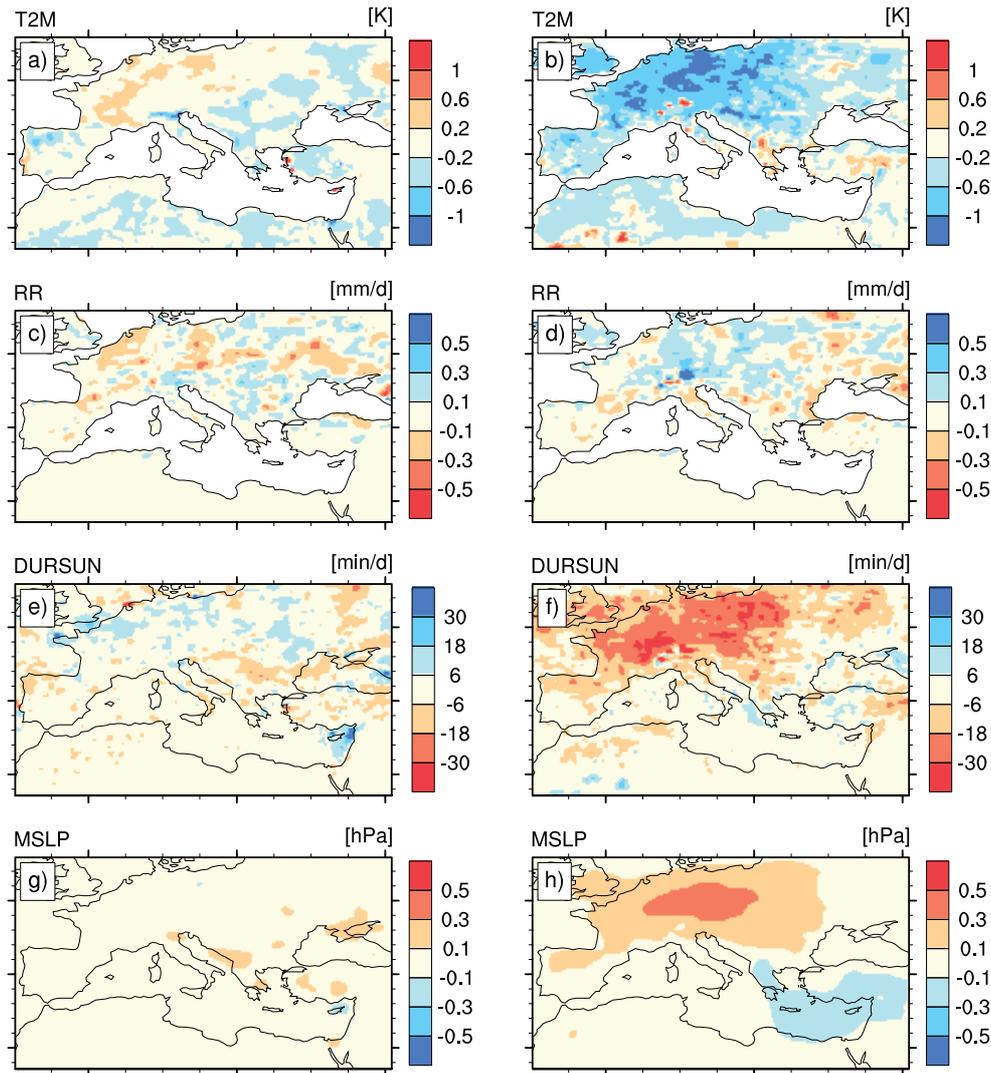
Figure 8: Same as Fig. 7, but for the summer season (JJA).

related to the changes in land use data reach $16 \, \text{W/m}^2$ (99th percentile value) with a sum of $0.6 \, \text{W/m}^2$ in winter and $26 \, \text{W/m}^2$ with a sum of $1.3 \, \text{W/m}^2$ in summer. Changes related to the soil data and soil model reach values of up to $19 \, \text{W/m}^2$ with a sum of about $5 \, \text{W/m}^2$ in winter and up to $32 \, \text{W/m}^2$ with a sum of about $0.1 \, \text{W/m}^2$ in summer. In both cases they are in line with changes in the surface energy partitioning indicated by the evaporative fraction EF.

The simulation GLC_HWSD shows for Mid-Europe an increase in SH and decrease in λH, which yields a decrease in EF and thus higher temperatures (as well as higher LW_{out}) can be expected. In Eastern Europe, the Balkans, and Turkey, increases in the evaporative fraction EF can be seen and a decrease in the 2-m temperature. The domain average difference between the simulations GLC_FAO and GLC_HWSD in EF is very close to zero. In the winter season (not shown), the EF of the GLC_HWSD simulation decreases in large parts of the domain, with a few exceptions in the Alps, the southern

parts of Spain, North Africa, and the Near East. The domain average value of the difference in EF is on the order of 0.15, resulting from a decrease in the latent heat flux (λH), which explains the unexpectedly higher differences in the 2-temperature in the winter/spring season.

For soil moisture near the field capacity, typical for the soil in spring after the snow melts, the soil hydraulic conductivity K differs between the considered water transport schemes by an order of magnitude. The Brooks and Corey BC64 model used in the extended TERRA_ML assumes a value of 0.15 for the volumetric soil moisture in coarse textured soil (sand), a higher K than in the Rijtema approach (see the supplementary material). Due to the faster water transport from the surface to the deep soil involved in the BC64 model, this results in less soil moisture near the surface. Compared to the summer season, when the latent heat flux is dominated by plant evapotranspiration, the dominating evaporation process in spring is bare soil evaporation, which depends on the near-surface

soil moisture. The modification of the soil hydraulic parameters therefore results in a different partition of the sensible and latent heat and explains the observed maximum in the model bias difference between the GLC_FAO/ECO_FAO and GLC_HWSD/ECO_HWSD realizations during the spring (Fig. 4). It is obvious that the impact is larger in regions where the snow's melting occurs regularly (AL, ME, EA). Since evaporation is part of the water cycle, an impact of the modified latent heat flux on precipitation as suggested by Fig. 5, showing a decrease of model precipitation bias in spring for the GLC_HWSD, cannot be neglected. The highest impact is in ME and EA, where the strongest response of evaporation is expected.

The area average differences in the climatic variables that can be related to the land use changes are generally small. Locally, however, within the areas with the largest changes in the land use data input, they reach 24 % in IP, 37 % in ME, and 50 % in AL for the monthly mean precipitation. Differences in the monthly mean temperature are up to 1.3 K in T_2M, 2.3 K in TX, and 1.5 K in TN.

Another question is whether the changes due to the differences in the soil and land use databases are more pronounced in climatically extreme years. Table 5 illustrates the changes obtained in the IP for the summer season (JJA). Presented are the changes in the area average seasonal values in the simulations ECO_FAO, GLC_HWSD and ECO_HWSD compared to the simulation GLC_FAO. Within the investigation period, 1991, 1994, and 1999 are dryer than the average, and 1992, 1995, and 1997 are wetter. The dry summer season of the IP was chosen because of the largest spread in the amount of precipitation between dry and wet years. In general, the differences in the temperature, precipitation, or surface energy partitioning between the wet and dry years are present but rather small.

Guillod et al. (2013) found that changes in temperature depend on changes in the soil texture. In the present investigation, the approach addressing the soil texture has been changed, rather than changing the texture category itself. Table 6 shows the changes in the simulation GLC_HWSD compared to the simulation GLC_FAO in ME for four soil texture categories. Again, the obtained changes are rather small. All changes have the same sign and the area average mean temperatures varies by up to 0.25 K, the precipitation changes by 0.1 mm/day, and changes in the turbulent fluxes are less than 5 W/m². Larger differences can be seen in the spread, indicating that locally the impact of the land use and soil data might be higher.

Changes in the soil data characteristics have a larger influence on the simulation results in areas with energy limited climate regimes than in regions with limited soil moisture. Seneviratne et al. (2010) discuss in detail the conceptual framework for the definition of soil moisture regimes. In the present paper, we define the moisture regimes with an EF up to 0.1 and the more energy limited regimes with an EF over 0.5.

Table 5: Area average of changes in the investigated variables (JJA mean) compared to the simulation GLC_FAO in the investigation area IP for wet years, for dry years, and for all investigated years.

	ECO_FAO	GLC_HWSD	ECO_HWSD
		All years	
T_2M [K]	0.10	0.70	1.11
TN [K]	0.11	0.85	1.21
TX [K]	0.10	0.46	0.92
RR [mm/d]	0.01	−0.10	−0.12
λH [W/m²]	−0.76	−6.72	−12.10
SH [W/m²]	0.53	4.99	8.39
LW$_{out}$ [W/m²]	0.46	3.84	6.16
E [kg/m²]	−0.03	−0.23	−0.42
		Dry years	
T_2M [K]	0.08	0.72	1.12
TN [K]	0.10	0.86	1.21
TX [K]	0.07	0.45	0.91
RR [mm/d]	0.01	−0.09	−0.11
λH [W/m²]	−0.49	−6.43	−11.65
SH [W/m²]	0.42	4.88	8.08
LW$_{out}$ [W/m²]	0.41	3.87	6.14
E [kg/m²]	−0.02	−0.22	−0.4
		Wet years	
T_2M [K]	0.10	0.70	1.12
TN [K]	0.11	0.84	1.21
TX [K]	0.12	0.49	0.96
RR [mm/d]	0.01	−0.10	−0.12
λH [W/m²]	−0.83	−6.88	−12.3
SH [W/m²]	0.55	4.94	8.51
LW$_{out}$ [W/m²]	0.46	3.82	6.25
E [kg/m²]	−0.03	−0.24	−0.42

Considering the entire domain, the differences in the area average mean temperature of the summer season between the simulations GLC_FAO and GLC_HWSD are up to 0.5 K higher in the energy limited climate regimes, which roughly encompass the parts of the modeling domain north of 44 ° latitude. No significant differences were found between the simulations GLC_FAO and ECO_FAO.

Fig. 10 displays the differences between the four performed CCLM simulations in the mean (1991–2000) volumetric soil water content (VWC) within the root zone (0.35 m) for both the winter (DJF) and the summer seasons (JJA). The simulations applying the same soil data but different land use input reveal only small differences in the VWC. In simulations that applied the new HWSD soil data, the VWC increases in the winter season are found in almost all regions, including areas north of the Black Sea, Spain, Italy, the Balkans, and Turkey. On the other hand, in Mid-Europe, including the Alpine area, a decrease of the VWC is visible. The pattern found in the summer season is similar but less pronounced. Compared to the simulated precipitation patterns (Fig. 7 and 8), a precipitation decrease is visible in the entire domain. In the summer season, both precipitation declines and in some areas precipita-
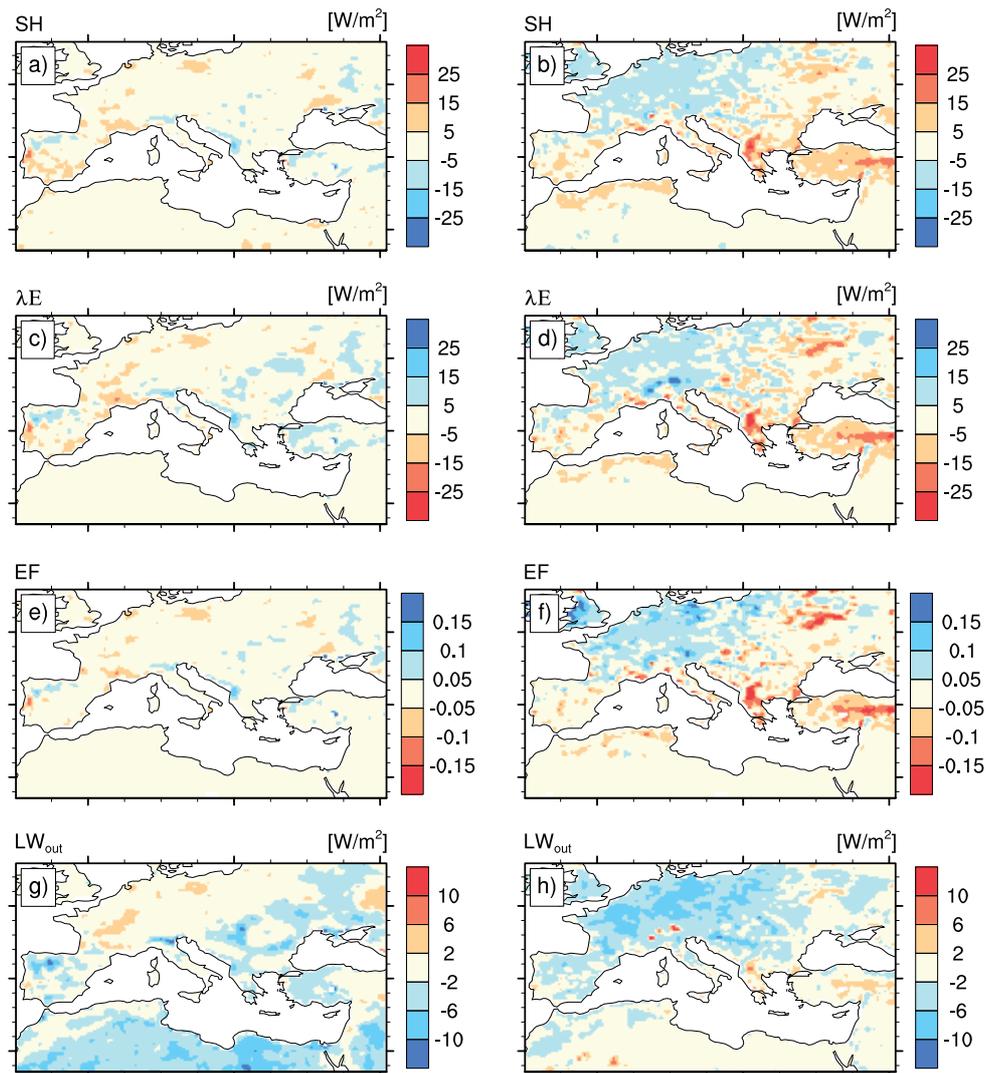
Figure 9: Differences between the model runs GLC_FAO and ECO_FAO (left column) and GLC_FAO and GLC_HWSD (right column) and the mean values for the summer season (JJA). a, b) SH c, d) λH e, f) EF and g, h) long wave upward radiation. Note the reversed color bars for λH and EF.

Table 6: Area average and spread of changes in the investigated variables (JJA mean) in the simulation GLC_HWSD compared to the simulation GLC_FAO in ME for different soil texture categories.

| Soil texture	All		Sand		Sandy loam		Loam		Loamy clay	
Grid cells	1217		86		243		762		120	
	mean	spread	mean	spread	mean	spread	mean	spread	mean	spread
T_2M [K]	0.93	1.12	0.86	0.68	0.73	0.75	0.99	0.93	0.96	0.38
TN [K]	1.22	1.27	1.18	0.85	1.03	0.91	1.29	1.12	1.21	0.47
TX [K]	0.60	1.26	0.53	0.73	0.39	0.97	0.67	1.05	0.65	0.55
RR [mm/d]	−0.08	0.71	0.01	0.52	−0.06	0.68	−0.09	0.61	−0.10	0.59
λH [W/m^2]	−6.82	27.10	−7.80	14.86	−3.32	20.45	−8.14	19.11	−4.92	11.98
SH [W/m^2]	7.50	21.67	8.30	12.84	4.70	15.52	8.52	16.17	6.21	9.33
LW$_{out}$ [W/m^2]	5.95	8.38	5.67	5.74	4.50	5.56	6.44	6.65	6.10	3.53
E [kg/m^2]	−0.24	0.94	−0.27	0.51	−0.11	0.71	−0.28	0.66	−0.17	0.41
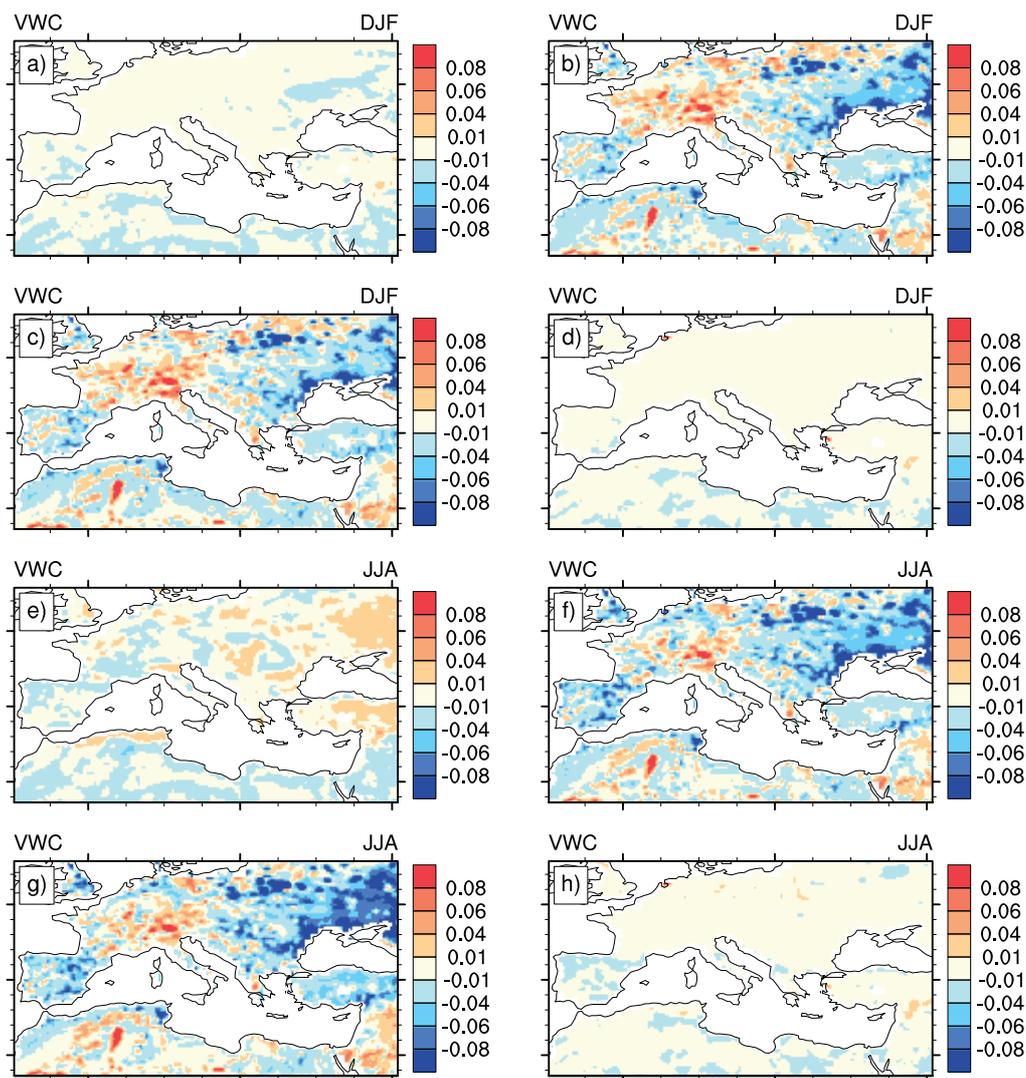
Figure 10: Difference in the volumetric soil water content (VWC) within the root zone (0.35 m) in the winter season (DJF). a) simulation GLC_FAO – ECO_FAO, b) GLC_FAO – GLC_HWSD, c) ECO_FAO – ECO_HWSD d) GLC_HWSD – ECO_HWSD and in the summer season (JJA) e) simulation GLC_FAO – ECO_FAO, f) GLC_FAO – GLC_HWSD, g) ECO_FAO – ECO_HWSD h) GLC_HWSD – ECO_HWSD.

tion increases are simulated. This is in agreement with GUILLOD et al. (2013), who found positive and negative moisture-precipitation couplings in simulations with different soil data inputs. SENEVIRATNE et al. (2010) give a detailed discussion of soil-moisture-climate interactions. On the other hand, HOHENEGGER et al. (2009) found in their simulations with CCLM in the Alpine area that the applied convection scheme influences the sign of the moisture-precipitation feedback. Nevertheless, with the recently implemented HWSD soil data, the CCLM is able to investigate this issue in much more detail.

Differences in the CCLM results that can be related to the land use changes are rather small. The differences resulting from the soil data and the soil data treatment in TERRA_ML are larger. They are within the range of the differences from using different lateral boundary forcings (e.g., SMIATEK (2014)). The key question how-

ever is if the changes found in the present investigation are significant. Fig. 11 shows the seasonal biases to the E-OBS reference of the runs GLC_FAO, ECO_FAO and HLC_HWSD in ME of T_2M, TN, TX, and RR in the context of the internal model variability. The internal variability has been assessed with the additional CCLM simulations GLC_FAO2/GLC_FAO3, ECO_FAO2/ECO_FAO3, and HLC_HWSD2/HLC_HWSD3 (see Table 2). For the changes in the soil data, the differences found in all seasons are significantly larger than the internal model variability and, thus, a significant impact on the simulation results can be assumed. Only in the summer season are the changes resulting from the different land use data larger than the internal model variability. This is, however, the season where surface processes have a larger impact on near-surface temperatures, as more radiative energy is available.
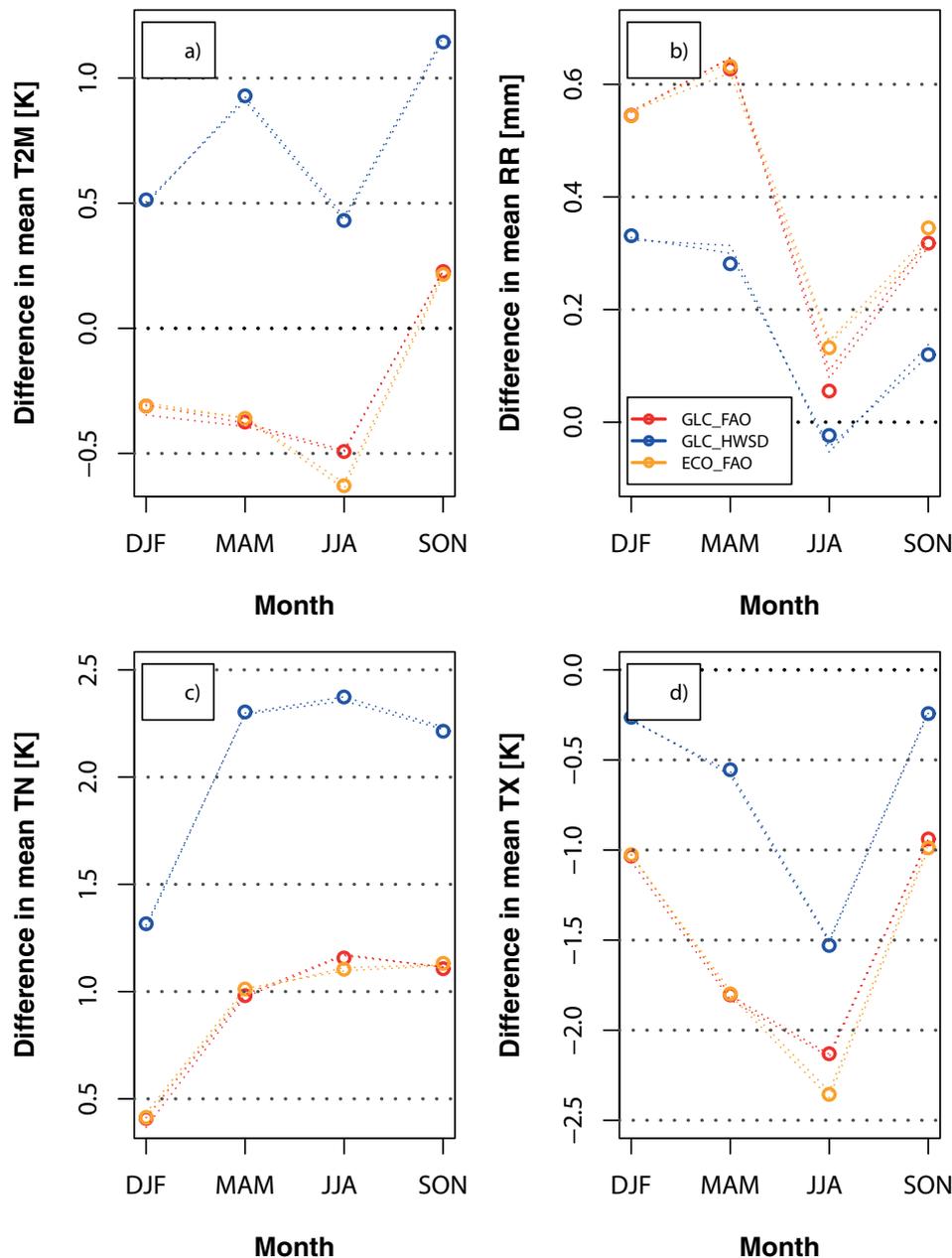
Figure 11: Difference between the simulated and E-OBS observed seasonal mean values in Mid-Europe for a) temperature T_2M b) precipitation RR, minimum temperature TN , and d) maximum temperature TX. Dotted lines show the internal model variability.

3   Conclusions

The present article evaluates the impact of time-invariant lower boundary data on the results of the CCLM regional climate model. For that purpose 15 year integrations (1986–2000) of the CCLM driven with ERA40 boundary data were performed with a resolution of 0.44 ° in the MED-CORDEX modeling domain. Soil data from the DSMW/FAO and HSWD databases as well as land use from the GLC2000 and the ECO-CLIMAP projects were investigated. The soil model TERRA_ML was extended to allow for the application of a regression analysis based on pedotransfer functions for soil hydraulic parameters. This approach requires an appropriately adapted bare soil evaporation scheme

and modifying the soil heat conductivity approach in TERRA_ML.

Biases to the observational E-OBS reference found in the investigated model runs indicate the suitability of the considered GLC2000 and ECOCLIMAP land use as well as the DSMW/FAO and HSWD soil data. Details in the results reveal only minor differences in the results obtained with CCLM runs that differ in the lower boundary land use and vegetation characteristics inputs employed. With maximum differences of up to 0.4 K in the mean 2-m temperature, 0.1 mm/d in mean precipitation, and 15 min/d in sunshine duration, all mean values for the period 1991–2000 are, with the exception of the summer season, within the range of the inter-

nal model variability. Locally, however, higher differences occur, of up to 1.3 K in the monthly mean temperature and up to 50 % in the monthly mean precipitation. Compared to the results obtained with the standard DSMW/FAO soil data, the differences obtained with the model runs employing the recently implemented HWSD soil data are larger: up to 1.8 K in the mean 2-m temperature, 0.4 mm/d (21 %) in the mean precipitation, and over 30 min/d in the sunshine duration. There are no significant differences in temperature, precipitation, and sunshine duration that could be related to the model inflow or outflow region, as found with the model internal variability.

With the present experiment it is not possible to disentangle model errors, reanalysis errors, errors in the observations, and the investigated invariant lower-boundary soil and land use inputs. It is therefore not possible to recommend a specific choice of land use and soil data input. Some indication however was found that the recently implemented HWSD soil data together with the extended soil model has the capability of reducing the model bias to the observational reference in some areas. Further investigation on this subject is needed.

Acknowledgments

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The pdf version (Adobe Java Script must be enabled) of this paper includes an electronic supplement:

Table of content – Electronic Supplementary Material (ESM)

1 HWSD Implementation in TERRA ML   **References to ESM**
Figure 1, 2
Table 1
Equations 1, 2, 3