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LETTER

Is land surface processes representation a possible weak link in current Regional Climate Models?

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Abstract

The representation of land surface processes and fluxes in climate models critically affects the simulation of near-surface climate over land. Here we present an evaluation of COSMO-CLM^2, a model which couples the COSMO-CLM Regional Climate Model to the Community Land Model (CLM4.0). CLM4.0 provides a more detailed representation of land processes compared to the native land surface scheme in COSMO-CLM. We perform historical reanalysis-driven simulations over Europe with COSMO-CLM^2 following the EURO-CORDEX intercomparison protocol. We then evaluate simulations performed with COSMO-CLM^2, the standard COSMO-CLM and other EURO-CORDEX RCMs against various observational datasets of temperature, precipitation and surface fluxes. Overall, the results indicate that COSMO-CLM^2 outperforms both the standard COSMO-CLM and the other EURO-CORDEX models in simulating sensible, latent and surface radiative fluxes as well as 2-meter temperature across different seasons and regions. The performance improvement is particularly strong for turbulent fluxes and for daily maximum temperatures and more modest for daily minimum temperature, suggesting that land surface processes affect daytime even more than nighttime conditions. COSMO-CLM^2 also alleviates a long-standing issue of overestimation of interannual summer temperature variability present in most EURO-CORDEX RCMs. Finally, we show that several factors contribute to these improvements, including the representation of evapotranspiration, radiative fluxes and ground heat flux. Overall, these results demonstrate that land processes represent a key area of development to tackle current deficiencies in RCMs.

1. Introduction

The processes occurring at the interface between the land and the atmosphere are involved in climate feedback mechanisms at various spatial and temporal scales and have a direct influence on humans and ecosystems living at this interface (Arneth *et al* 2010, Seneviratne *et al* 2010). Conversely, the land surface is continuously transformed by human activities through land management and land cover changes thus exerting a direct anthropogenic forcing on climate. The representation of land surface processes is therefore a crucial component of climate models. Land Surface Models (LSMs) used in climate simulations have been gradually improved over the last four decades to include more complex and more physically-based parametrizations (van den Hurk *et al* 2011, Clark *et al* 2015). While there are sparse indications that the historical development of LSMs has improved the simulated land surface fluxes in offline mode (mainly illustrated by the better performance of last generation LSMs compared to the first generation 'bucket' model (Best *et al* 2015, Chen *et al* 1997)), there is still a lack of formal evidence that this has translated into overall better climate model performance. This calls for more systematic evaluations of LSMs in coupled mode to examine the relationship between the realism of land surface processes representation and overall climate model performance.

Table 1. EURO-CORDEX RCMs used.

Model	Institution	LSM
ALADIN 5.2	HMS	ISBA (Noilhan and Planton 1989, Douville *et al* 2000)
HIRHAM 5	DMI	(Hagemann 2002)
WRF 3.3.1	IPSL-INERIS	NOAH (Ek *et al* 2003)
RACMO 2	KNMI	HTESSEL (Balsamo *et al* 2009)
HadRM 3P	MOHC	MOSES (Cox *et al* 1999)
RCA 4	SMHI	(Samuelsson *et al* 2006)
REMO 2009	MPI-CSC	(Hagemann 2002, Rechid *et al* 2009)
RegCM 4.3	ICTP	BATS (Dickinson 1984)
COSMO-CLM 4.8.17	CLM-Community	TERRA_ML (Doms *et al* 2011)
COSMO-CLM^2	ETH Zurich	CLM4.0 (Oleson *et al* 2010, Lawrence *et al* 2011)

Regional Climate Models (RCMs) offer an ideal testbed for investigating this issue. Firstly, because RCMs operate in a more constrained 'space' as opposed to free-running global models, a direct 'day-to-day/year-to-year' comparison with observations is possible and meaningful. Indeed, using reanalysis as lateral boundary conditions to drive RCMs ensures a consistency between the simulated and observed synoptic conditions, while thermodynamic feedbacks (importantly those involving land processes) are still allowed to respond within this dynamically constrained system (Giorgi 2006). Secondly, RCMs are typically run at finer resolution than global models, thus reducing the gap between the resolved scale and the scale at which land processes actually operate. Thirdly, there is indeed scope for significantly improving land processes representation in current RCMs since they tend to include relatively simple LSMs not reflecting the most recent advances in land surface modelling (Davin *et al* 2011). The heritage of RCMs, which are often based on existing or pre-existing weather forecast models, can at least partly explain the larger weight given to atmospheric compared to land processes development in these models. Against this background, it is legitimate to ask whether the long-standing systematic biases which have been reported in successive generations of RCM intercomparisons, in particular in the case of Europe (Hagemann *et al* 2004, Jacob *et al* 2007, Christensen *et al* 2007, Kotlarski *et al* 2014), could be in part due to land processes representation.

In this study, we evaluate RCM simulations performed in the framework of the international intercomparison project EURO-CORDEX. For one of the EURO-CORDEX models, COSMO-CLM, we additionally perform a simulation in which the standard land surface scheme is replaced by a more advanced LSM. By doing so, the assessed differences between the two COSMO-CLM experiments highlight the role of land process representation. These differences are assessed in the context of the EURO-CORDEX multi-model spread, thus indicating the extent to which land processes can impact model performance compared to other RCM aspects.

2. Methods

2.1. EURO-CORDEX RCMs

We evaluate reanalysis-driven RCM simulations performed as part of the EURO-CORDEX project and downloaded from the Earth System Grid Federation (ESGF) archive. The nine RCMs considered (table 1) provided simulations at 50 km (0.44 degree on a rotated grid) spatial resolution on a common analysis domain encompassing Europe in its entirety. The 6-hourly ERA-Interim reanalysis (Dee *et al* 2011) is used in all models to prescribe lateral boundary conditions and sea surface temperatures. The longest period common to all models (1990-2008) is used for the analyses.

2.2. COSMO-CLM^2

In addition to the aforementioned official EURO-CORDEX simulations we also analyse a simulation performed with COSMO-CLM^2. COSMO-CLM^2 is an alternative configuration of COSMO-CLM featuring a different LSM.

COSMO-CLM is a non-hydrostatic regional atmospheric model jointly developed by the COnsortium for Small-scale MOdelling (COSMO) and the Climate Limited-area Modelling Community (CLM-Community) and is one of the participating EURO-CORDEX RCMs (table 1). In its standard configuration, COSMO-CLM includes TERRA_ML as its LSM. In COSMO-CLM^2, however, TERRA_ML is replaced by the more complex Community Land Model (CLM). Earlier versions of COSMO-CLM^2 where based on CLM3.5 coupled as a sub-routine to COSMO-CLM (Davin *et al* 2011, Davin and Seneviratne 2012). Here we use the more recent version CLM4.0 (Oleson *et al* 2010, Lawrence *et al* 2011) coupled to COSMO-CLM via the OASIS3-MCT coupler (Valcke *et al* 2013).

The main conceptual differences between TERRA_ML and CLM4.0 concern both biogeophysical and hydrological processes. Unlike in TERRA_ML, an explicit canopy layer is considered in CLM4.0, resulting in specific vegetation temperature and fluxes. The linkage between transpiration and photosynthesis is considered in CLM4.0 while an empirical formulation

Table 2. Reference gridded datasets used for evaluation. The time period does not refer to the maximum coverage but to the time period used in the analysis maximizing the overlap with the EURO-CORDEX models.

Dataset	Variables	Resolution	Time period	Reference
CRU TS3.22	2-m temperature precipitation cloud cover	0.5 × 0.5	1990-2008	(Harris *et al* 2014)
E-OBS v11	2-m temperature precipitation	0.5 × 0.5	1990-2008	(Haylock *et al* 2008)
GPCP2.2	precipitation	2.5 × 2.5	1990-2008	(Huffman *et al* 2009)
FLUXNET MTE	latent heat sensible heat	0.5 × 0.5	1990-2008	(Jung *et al* 2011)
LandFlux-EVAL	latent heat	1 × 1	1990-2005	(Mueller *et al* 2013)
SRB3.0	shortwave radiation longwave radiation	1 × 1	1990-2007	(Zhang *et al* 2015)
CERES	shortwave radiation longwave radiation	1 × 1	2001-2008	(Rutan *et al* 2015)

of stomatal conductance is used in TERRA_ML. Subgrid scale surface heterogeneity is ignored in TERRA_ML and is represented using a tile approach in CLM4.0. CLM4.0 additionally considers groundwater and calculates runoff taking into account sub-grid scale topographic heterogeneity using a TOPMODEL-based approach. A more complete description of CLM4.0 and its input datasets is provided in Oleson *et al* (2010). In the present study, CLM4.0 is used in its biogeophysics-only configuration without carbon and nitrogen dynamics. The only modification we included to CLM4.0 concerns two hydrological parameters influencing surface and subsurface runoff (i.e., exponential decay factor influencing the saturation excess component of surface runoff and maximum subsurface drainage). Namely, we reverted to the values used in CLM3.5 for these parameters (Lawrence *et al* 2011) since preliminary tests indicated slightly more realistic evapotranspiration rates over Europe for this parameter choice.

The simulation performed with COSMO-CLM^2 follows the EURO-CORDEX protocol and is a sister simulation of the one performed with COSMO-CLM (table 1). That is, the same model version and model parameter set are used for the atmospheric component, the only difference being the LSM used. In doing so, comparing the COSMO-CLM and COSMO-CLM^2 simulations strictly isolates the effect of land processes representation, all else being identical.

2.3. Evaluation datasets

The various reference products used for evaluation are described in table 2. The selected products cover temperature, precipitation and surface heat and radiation fluxes. When possible, different products are considered for a given variable in order to account for uncertainties in observation-based datasets. All the products are used at a monthly resolution and were regridded, using bilinear interpolation, to a common half-degree regular grid for comparison with the EURO-CORDEX models. For products not covering the full 1990-2008 EURO-CORDEX common analysis period a shorter time period is used instead.

3. Results

3.1. Overall model performance

In this section, we evaluate overall RCM performance using synthetic scores applied over the entire European continent. Model performance with respect to temperature, precipitation and surface fluxes is assessed for each of the EURO-CORDEX RCMs (figure 1). As in Davin and Seneviratne (2012), a root-mean-square error (RMSE) is calculated at all grid cells based on monthly values over a multi-year period (period depending on reference product, see table 2) thus integrating both temporal and spatial performance. When possible, different reference products are used for a given variable, because the choice of reference product is likely to have a major influence on the inferred scores beyond all other methodological choices (Schwalm *et al* 2013).

Considering first surface fluxes, the coupling with CLM4.0 dramatically improves the performance of the standard COSMO-CLM (figure 1(a)). COSMO-CLM^2 outperforms not only COSMO-CLM but also most other EURO-CORDEX RCMs for both radiative and turbulent fluxes. In some cases (e.g. for evapotranspiration) COSMO-CLM^2 also outperforms the EURO-CORDEX multi-model mean (MMM). This result highlights the added value of using a more advanced LSM compared to the simpler schemes commonly used in current RCMs. In line with Best *et al* (2015), we also note that most models typically have larger errors for sensible heat flux than for latent heat flux.

As a consequence of the better representation of surface fluxes, 2-meter temperature is also better simulated in COSMO-CLM^2 (figure 1(b)), which outperforms the standard COSMO-CLM as well as most other RCMs. The improvement is particularly

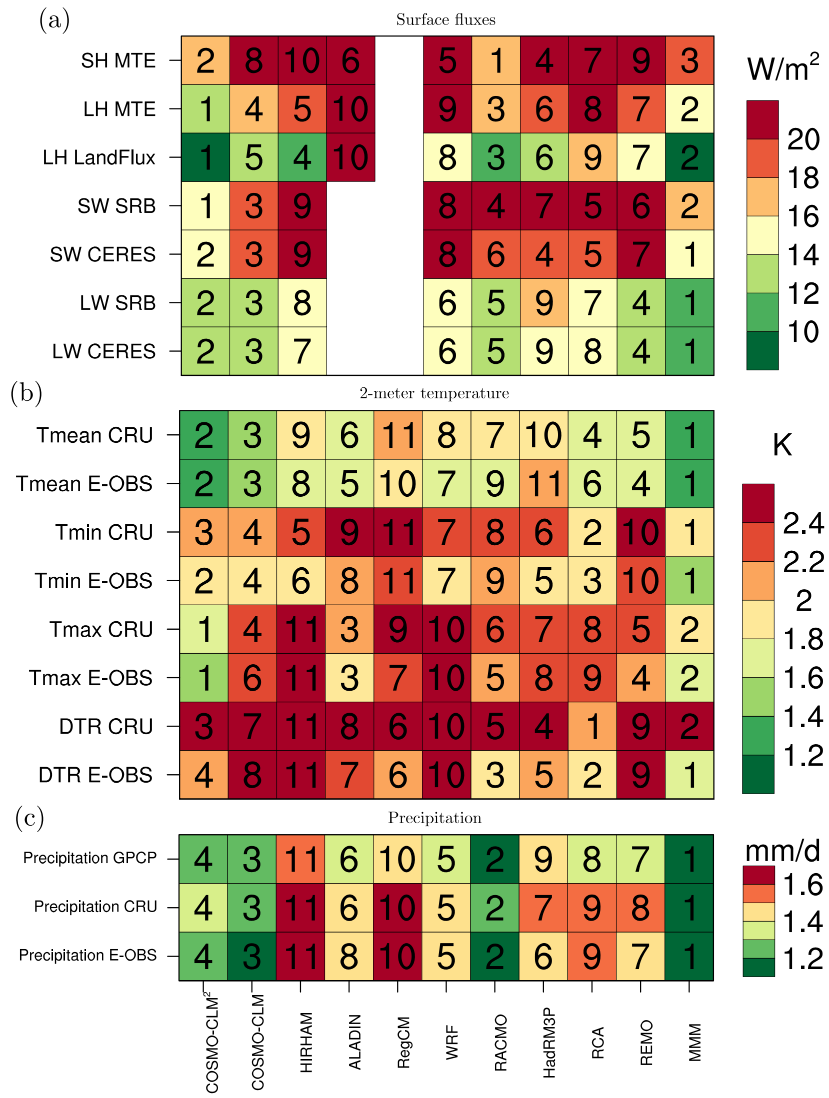

Figure 1. RMSE-scores (colour) and model ranking (numbers) integrating both spatial and temporal model performance. RMSEs are calculated across all land grid points over Europe (-10W 30E; 36 N 70N) based on monthly values over multiple years. MMM: multi-model mean of EURO-CORDEX excluding COSMO-CLM^2.

substantial for maximum temperature (monthly average of daily maximum temperature) indicating that the representation of land processes influences daytime more than nighttime conditions. While the Diurnal Temperature Range (DTR) is also improved in COSMO-CLM^2, it is interesting to note that absolute errors are typically higher for DTR than for other metrics (e.g. Tmax) indicating that the representation of the diurnal cycle is a critical remaining deficiency in current RCMs.

No improvement, however, is seen for precipitation which is even slightly degraded (figure 1(c)). In view of the multi-model spread this degradation remains relatively minor as COSMO-CLM and COSMO-CLM^2 still cluster together in terms of ranking. This degradation for precipitation might seem counterintuitive given that both surface temperature and surface fluxes are generally improved in the model. In this respect, we note that atmospheric parameters in the model have been tuned in the context of TERRA_ML and not of CLM4.0. We therefore expect that a retuning would be necessary to obtain optimal performances in particular in terms of precipitation. This is, however, not the scope of this study as a different atmospheric setup would make the attribution of assessed differences to land processes more difficult.

For comparison purpose, we also performed the same multi-variate ranking procedure including in addition an earlier version of COSMO-CLM^2 evaluated in Davin and Seneviratne (2012) and based on CLM3.5 instead of CLM4.0 (figure S1). The coupling with CLM3.5 already improves overall model performance compared to COSMO-CLM, while switching to CLM4.0 provides further improvements compared to CLM3.5 in line with global offline evaluation results (Lawrence *et al* 2011).

The only difference between COSMO-CLM^2 and COSMO-CLM being the LSM used, the overall better performance of COSMO-CLM^2 can be attributed to the representation of land processes. This

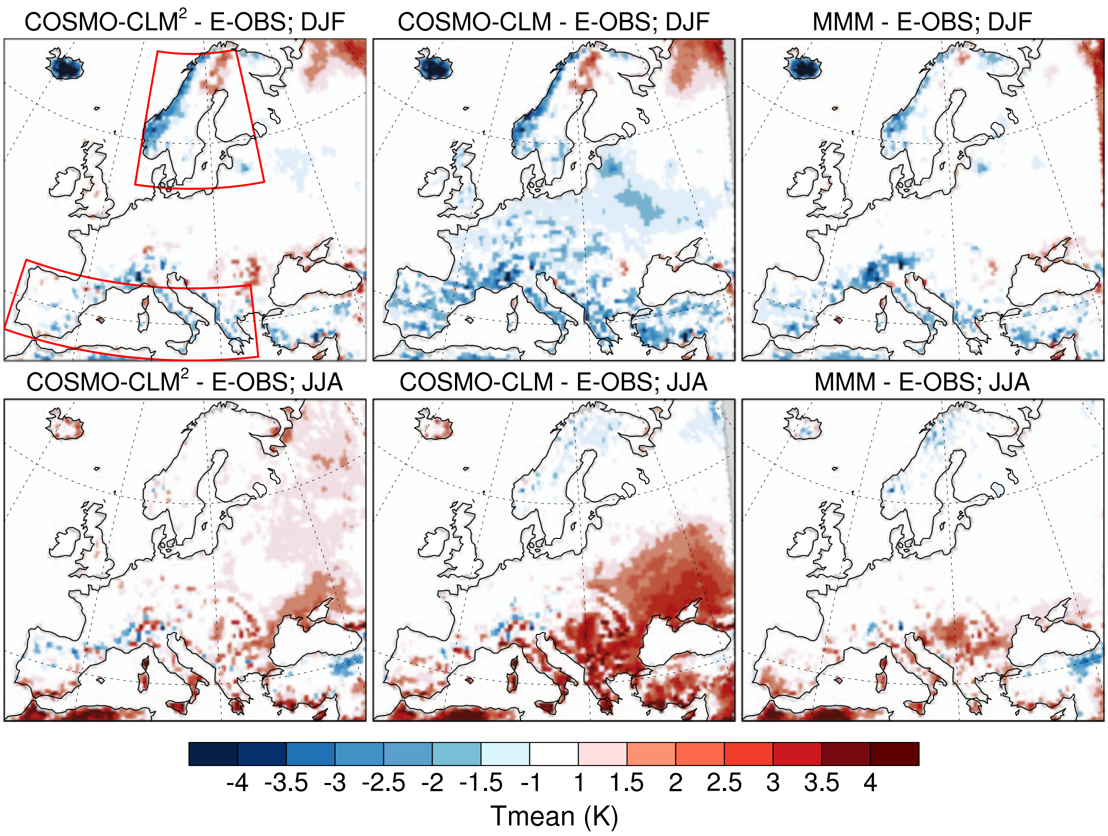

Figure 2. 2-metre temperature bias (model minus E-OBS) for COSMO-CLM, COSMO-CLM^2 and the EURO-CORDEX Multi-Model Mean (MMM). Indicated in red in the first panel are the two regions used for analysis and defined as in the PRUDENCE project (Christensen *et al* 2007), the southern region being a combination of two of the original PRUDENCE domains.

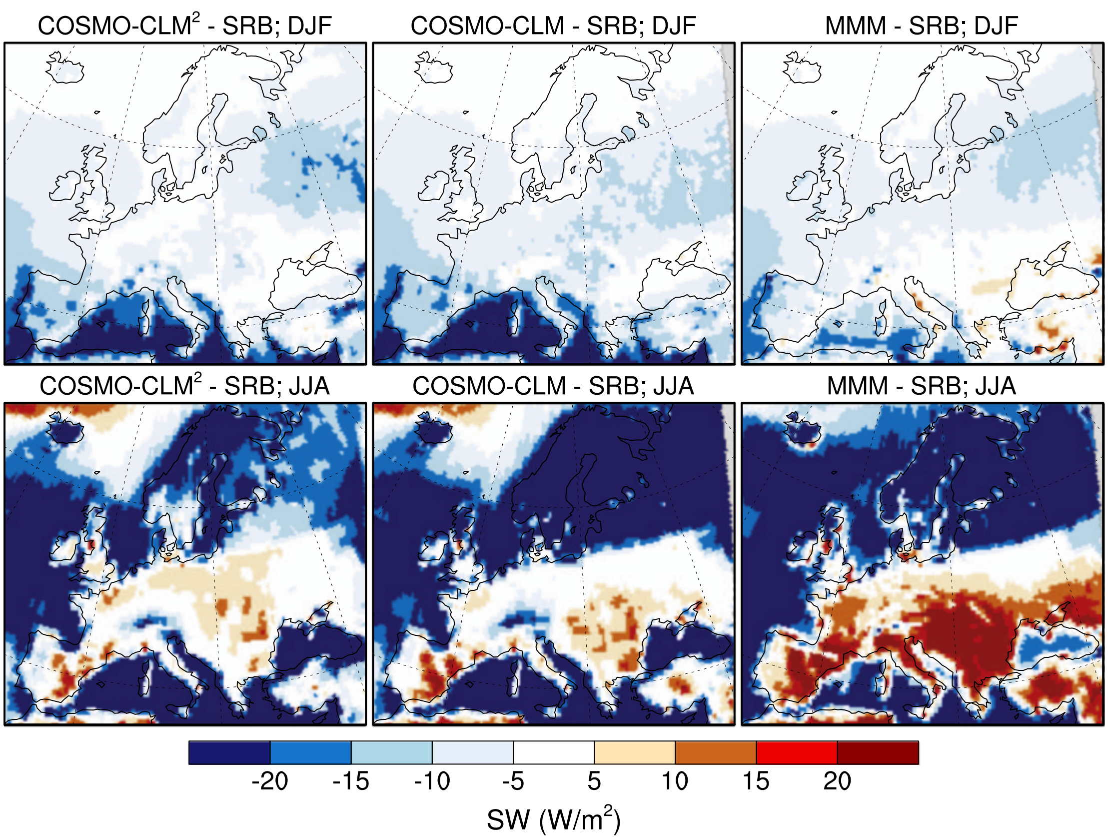

Figure 3. Same as figure 2 for net shortwave radiation and using SRB as reference product.

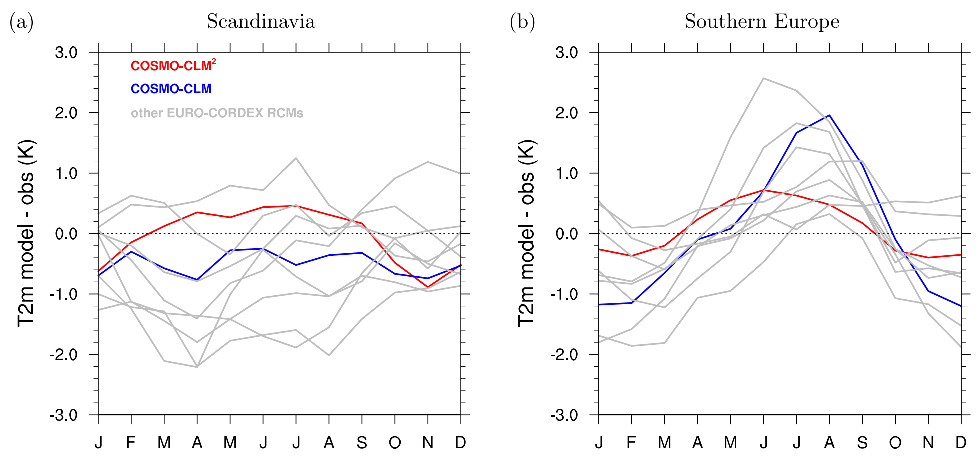

Figure 4. Seasonal cycle of 2-metre temperature bias (model minus E-OBS) for (a) Scandinavia and (b) Southern Europe (combining the Mediterranean and Iberian Peninsula as defined in the PRUDENCE project).

interpretation is further supported by the more realistic surface fluxes simulated in COSMO-CLM^2 as shown in this section. In the next section, we examine more specifically the nature of the model biases to better characterize the mechanisms at play.

3.2. Origin of model biases

The sign and magnitude of model biases is generally not uniform across Europe and in particular a North-South contrast is visible for temperature (figure 2), radiation (figure 3) and other variables (Supplementary figures). For this reason, we focus our analyses on two regions representative of Southern and Northern Europe (boundaries displayed in figure 2) in addition to the bias maps provided in figures 2, 3 and in the Supplementary Information.

Over Northern Europe, most RCMs underestimate temperature in particular in spring and summer (figure 4(a)), a tendency mostly affecting daytime temperatures (figures S2–4). This bias reflects a systematic underestimation of surface shortwave radiation (figure 3; figure S6) in turn linked to a tendency of the RCMs to overestimate cloud cover (figure S8). We note an inter-model correlation between summer temperature and net shortwave radiation of 0.7 over Scandinavia, thus confirming that the cause of temperature biases in this region is essentially of radiative origin. While atmospheric processes are obviously critical for cloud cover biases, land processes may also play a role by indirectly modulating cloud formation through energy partitioning at the surface (Davin *et al* 2011). All the EURO-CORDEX models in fact overestimate summer evaporative fraction over the northern half of Europe (figure S11). COSMO-CLM^2 alleviates this problem compared to COSMO-CLM which implies reduced water input to the atmosphere with beneficial effects on simulated cloud cover and net shortwave radiation (figure 3), as previously found in earlier model versions (Davin *et al* 2011, Davin and Seneviratne 2012).

In contrast, warm biases dominate in summer over Southern Europe (figure 2; figure 4(b)) in conjunction with an overestimation of interannual summer temperature variability (figure 5(c)). This persistent deficiency has been reported in previous RCM intercomparisons and attributed to excessive summer drying (Hagemann *et al* 2004, Christensen *et al* 2007, Hirschi *et al* 2007, Vautard *et al* 2013, Kotlarski *et al* 2014). Most EURO-CORDEX RCMs indeed strongly underestimate summer evapotranspiration over the Mediterranean region (figure 5(a)) and the magnitude of this underestimation correlates well with temperature biases across models (figure 5(c)). Both the evapotranspiration bias and the resulting temperature bias are largely alleviated in COSMO-CLM^2 compared to COSMO-CLM and other RCMs confirming that land processes representation plays a major role in this long-standing deficiency. One possible factor in this improvement is that CLM4.0, unlike the other models considered here, includes a representation of groundwater which can limit the excessive summer drying. Another hypothesis is that COSMO-CLM, as most other RCMs, generally overestimates evapotranspiration when water is not limited (this is for instance the case in the spring for Southern Europe but this happens also more generally over Northern Europe as mentioned previously), thus leading to depleted water conditions later in summer. COSMO-CLM^2 exhibits a more conservative water use behaviour in the spring letting more water available for transpiration in the following summer. This might have a physical cause (e.g. higher aerodynamic resistance) or a physiological cause linked to the explicit link between transpiration and photosynthesis represented in CLM4.0.

Another aspect playing a role in seasonal temperature variations over southern Europe is the representation of ground heat flux (GHF). Most models tend to overestimate the annual temperature range, with too low temperatures in winter and the opposite

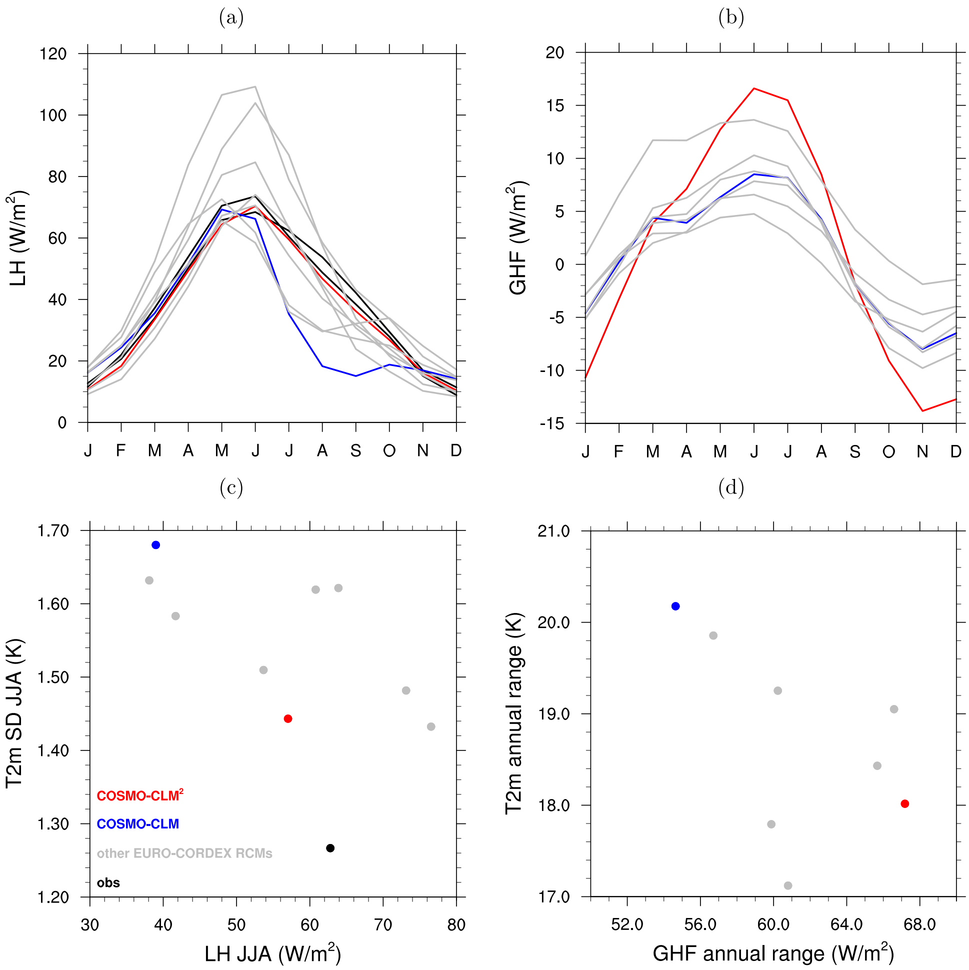

Figure 5. Mean seasonal cycle of (a) latent heat flux (LH) and (b) ground heat flux (GHF) over Southern Europe. Inter-model relationships (c) between summer temperature interannual variability and summer latent heat flux and (d) between annual temperature range and GHF annual amplitude (d) for Southern Europe. Reference datasets shown in black are LandFlux-EVAL and FLUXNET MTE (a) and E-OBS and FLUXNET MTE (c). GHF is not provided on the ESGF archive and is therefore calculated as the residual of the surface energy balance implicitly assuming that models conserve energy at the land-atmosphere interface.

in summer (figure 4(b)). This problem is notably reduced in COSMO-CLM^2, which strikingly also exhibits a larger GHF annual amplitude (figure 5(b)). A larger amplitude means that more energy is stored into the ground during summer and subsequently more energy can be released to the atmosphere the following winter. This results in a dampened annual cycle of temperature as the additional energy stored into the ground cannot be used to warm near-surface air in summer but can be released in winter and limits then the winter cooling. The deeper bottom boundary condition (42 m) for thermal calculations in CLM4.0 compared to other models (usually not more than 10 meters) results in a larger soil volume and heat storage capacity that can explain the larger annual range in GHF. Supporting this interpretation of the important role of GHF, we also find a relatively good inter-model relationship between the simulated annual temperature range and GHF (figure 5(d)). In other words, models with low GHF annual amplitude tend to overestimate more the annual temperature range. Previous studies already highlighted the importance of placing the bottom boundary condition for thermal calculations much deeper than 10 metre to adequately represent GHF and soil temperature dynamics over seasonal and decadal time scales (Smerdon and Stieglitz 2006, MacDougall *et al* 2008, 2010).

4. Conclusions

Despite decades of improvement, RCMs still suffer from large systematic biases. In the case of Europe, these biases have been exposed in successive generations of model intercomparisons (Hagemann *et al* 2004, Jacob *et al* 2007, Christensen *et al* 2007, Kotlarski *et al* 2014). Here we argue that one of the most promising way forward for reducing these biases is to tackle deficiencies in modelled land-atmosphere processes. Based on an evaluation of reanalysis-driven RCM simulations from the EURO-CORDEX multi-model ensemble, we show that land processes play a central role in many long-standing issues affecting RCM performance. By coupling the COSMO-CLM

RCM to a state-of-the-art LSM we furthermore show that the model performance in simulating surface fluxes and climate can be dramatically improved, to the extent that this coupled system outperforms most other EURO-CORDEX RCMs for a range of simulated variables.

In general, temperature biases over Northern Europe are radiation-driven and land processes are found to play a role through an indirect mechanism involving turbulent energy partitioning at the surface with a subsequent effect on cloud cover and radiation. In contrast, temperature biases over Southern Europe involve more direct couplings (1) between evapotranspiration and surface temperature and (2) between GHF and surface temperature. The latter aspect, which has been underappreciated so far, is found to be important for simulating a realistic amplitude of the temperature annual cycle. This calls for a large-scale synthesis of GHF measurements which would enable to better constrain ground heat dynamics in the models. Finally, this study illustrates the benefit of taking an extended approach to model evaluation that includes the full surface energy balance perspective to help understand the origin of model deficiencies and guide future model development.

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