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Land-atmosphere interactions in sub-polar and alpine climates in the CORDEX FPS LUCAS models: I. Evaluation of the snow-albedo effect

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Abstract

In the Northern Hemisphere, the seasonal snow cover plays a major role in the climate system via its effect on surface albedo and fluxes. The parameterization of snow-atmosphere interactions in climate models remains a source of uncertainty and biases in the representation of the local and global climate. Here, we evaluate the ability of an ensemble of regional climate models (RCMs) coupled to different land surface models to simulate the snow albedo effect over Europe, in winter and spring. We use a previously defined index, the Snow Albedo Sensitivity Index (SASI), to quantify the radiative forcing due to the snow albedo effect. By comparing RCM-derived SASI values with SASI calculated from reanalyses and satellite retrievals, we show that an accurate simulation of snow cover is essential for correctly reproducing the observed forcing over mid- and high-latitudes in Europe. The choice of parameterizations with first and foremost the choice of the land surface model but also the convection scheme and the planetary boundary layer, strongly influences the representation of SASI as it affects the ability of climate models to simulate snow cover correctly. The agreement between the datasets differs between the accumulation and ablation periods, with the latter one presenting the greatest challenge for the RCMs. Given the dominant role of land surface processes in the simulation of snow cover during the ablation period, the results suggest that the choice of the land surface model is more critical for the representation of SASI than the atmospheric model during this time period.

https://doi.org/10.5194/tc-2021-290
Preprint. Discussion started: 18 October 2021

1. Introduction

Snow is an important part of the climate system as it regulates the temperature of the Earth's surface via its effect on surface albedo and surface fluxes. In mid- and high-latitude regions, snow is the main interface through which land interacts with the atmosphere during the cold season and the importance of snow-atmosphere interactions in modulating the energy budget at high latitudes during winter has been demonstrated (Diro and Sushama, 2018; Henderson et al., 2018; Xu and Dirmeyer, 2013). Snow cover extent and depth can modify both surface energy and moisture budgets, triggering complex feedback mechanisms that impact both local and remote climates (Diro and Sushama, 2018). In particular, snow can have a strong impact on climate due to its high albedo, primarily because of the contrast in the surface energy balance between snow-covered and snow-free land surfaces (Qu and Hall, 2014). Reciprocally, with climate change, rising temperatures are already altering the Earth's snow amount and occurrences, for example shortening the snow season in Eurasia (Ye and Cohen, 2013; Gobiet et al., 2014; Mioduszewski et al., 2015; Beniston et al., 2018; Matiu et al., 2020). In this context, it is crucial to better understand snow-atmosphere processes and the ability of climate models to represent them.

The direct impact of snow on the atmosphere is known as the snow albedo effect (SAE; Xu and Dirmeyer, 2011, 2013), where the presence of snow affects the land surface energy budget and influences the local climate, modifying air temperature. To quantify the contribution from the SAE to the snow-atmosphere coupling, Xu and Dirmeyer (2011) developed the Snow Albedo Sensitivity Index (SASI). This index combines incoming shortwave radiation with snow cover variability to quantify the snow-albedo coupling strength, i.e. SASI estimates the degree to which the atmosphere responds to anomalies in snow cover. Applying SASI to satellite observations, Xu and Dirmeyer (2011) found that the coupling between snow and albedo is particularly strong during the snowmelt period in the Northern Hemisphere. At high-latitudes, for example, the effects of snow cover on the climate is strongly related to the way vegetation cover is prescribed. Removal of boreal forests locally reduces surface air temperature and precipitation by increasing surface albedo and decreasing plant evapotranspiration. The strength of the coupling between snow and the atmosphere is determined by processes involving radiative fluxes but also hydrology. Therefore, Xu and Dirmeyer (2013) also defined the snow hydrological effect (SHE), which is a result of soil moisture anomalies from snowmelt. Through land-atmosphere interactions, they have a delayed impact on the atmosphere. Besides these direct and indirect effects, positive and negative snow-atmosphere feedbacks, such as the snow-albedo feedback (SAF; Qu and Hall, 2007; Fletcher et al., 2015; Thackeray et al., 2018) can amplify anomalies. The SAF represents changes in surface albedo from cooling (warming) that can cause decreases (increases) in absorbed solar radiation, amplifying the initial cooling (warming). It is an important driver for regional climate change in Northern Hemisphere land areas.

Here, we investigate the ability of an ensemble of RCMs to represent snow cover and the radiative forcing from the snow albedo effect (SASI) over Europe, including a comparison between mid- and high-latitude regions. We derive SASI using radiative fluxes and snow cover from satellites, reanalysis and model outputs. Building on findings by Xu and Dirmeyer (2011, 2013), we focus on winter and spring seasons, i.e. transitioning from the accumulation to the ablation period, when SASI is reaching a maximum. While some previous studies have investigated snow-atmosphere processes in climate models for specific regions (e.g. European Alps; Magnusson et al., 2010; Matiu et al., 2019; Lüthi et al., 2019), the literature remains limited. Here, we use the RCMs outputs from the flagship pilot study Land Use and Climate Across Scale (LUCAS; Rechid et al., 2017; Breil et al., 2020; Davin et al., 2020; Reinhart et al., 2020; Sofiadis et al., 2021). It is endorsed by the Coordinated Regional Climate Downscaling Experiment (CORDEX) of the World Climate Research Programme (WCRP) over the European domain (EURO-CORDEX, Jacob et al., 2020) and it enables us to perform a broader assessment of several RCMs within a consistent framework. Our assessment is carried out in two parts and published in companion articles. In Part I, we investigate the ability of these RCMs to represent the SASI under present-day land cover distribution, while in Part II we explore the effects of large-scale changes in vegetation cover. In LUCAS, each RCM performed three coupled land-atmosphere experiments at the European scale: two idealized and intensive land use change experiments (GRASS and FOREST) and a control experiment (EVAL). The GRASS and FOREST experiments will be

https://doi.org/10.5194/tc-2021-290
Preprint. Discussion started: 18 October 2021

examined in the companion paper (Part II) while here, we use ten models from the EVAL experiment only, which employ their standard land use and land cover maps.

Section 2 introduces the modeling and observational datasets used in this study as well as the derivation of SASI, while Section 3 examines and discusses the ability of climate models to represent SASI compared with satellite observations and reanalyses, focusing on the strength and timing of the signal. Further, the origin of the differences between the models are explored by evaluating potential common biases in the ensemble of simulations as well as individual model biases. The analysis also explores the differences in SASI between mid- and high-latitude regions, opening the discussion on the impacts of different land cover for the simulation of SASI, which will be further explored in Part II. Finally, Section 4 the last sections offer some concluding remarks.

2. Data and methodology

2.1 LUCAS experiments and models

2.1.1 The LUCAS experiments

The simulations from the flagship pilot study LUCAS simulations cover the standard EURO-CORDEX domain (Jacob et al., 2014) with a horizontal grid resolution of 0.44° (around 50 km). All RCMs in LUCAS use a rotated coordinate system except the RegCM model, which applies a Lambert conformal projection (suitable for mid-latitudes) on a regular grid. Here we use outputs from the EVAL experiment, which employ land use and land cover maps; the GRASS and FOREST experiments will be examined in the companion paper (part II). All simulations span the period 1986–2015 (with a spin-up period ranging from one up to six years depending on the model) and take lateral and boundary conditions from the ERA-Interim reanalysis (Dee et al., 2011). More details can be found in Davin et al. (2020).

2.1.2 Models and configurations

We use outputs from ten coupled surface-atmosphere RCM simulations that participated in the LUCAS project. The main model characteristics that are important for snow albedo coupling are summarized in Table 1. The model ensemble presents five different RCMs: COSMO-CLM version 5.0-clm9 (Sørland et al., 2021), WRF version 3.8.1 (Skamarock et al., 2008), RegCM versions 4.6 and 4.7

(Giorgi et al., 2012), RCA4 (Strandberg et al., 2015) and REMO (Jacob et al., 2012). These RCMs contributed with different setups and configurations as described in Table 1. For example, the same RCM is coupled to different land surface models (LSMs): COSMO-CLM is coupled to three distinct LSMs, which are CLM5.0 (Lawrence et al., 2020), VEG3D (Breil and Schadler, 2017) and TERRA-ML (Schrodin and Heise, 2002). WRF is coupled with either CLM4.0 (Oleson et al., 2010) or NOAH-MP (Niu et al., 2011). Vice versa, the same LSM is combined with different versions of RCMs. The CLM4.5 (Oleson et al., 2013) LSM is coupled to two distinct versions of RegCM (4.6 and 4.7) which also differ in their choice of convection schemes. There are also two institutes with the same RCM and LSM (WRF and Noah-MP) but different parameterizations, as they use distinct planetary boundary layer (PBL) schemes. A detailed description of the RCMs is provided by Davin et al. (2020). For the analyses in the present study, we use daily and monthly model outputs for incoming shortwave radiation and snow cover. For deriving SASI, the native grid of the models was kept, minimising data loss. The other fields were interpolated to a common 0.5°x0.5° grid using Climate Data Operators (CDO) bilinear remapping.

2.1.3 Snow-buried fraction of vegetation in models

At high-latitudes, the effects of snow cover on regional climate strongly depend on the prescribed vegetation cover. Removal of boreal forests locally reduces surface air temperature and precipitation by increasing surface albedo and the duration of the snow cover and by decreasing plant evapotranspiration. Today, the role of forest albedo on winter-spring climate in the high-latitudes is well acknowledged based on field campaigns such as the Boreal Ecosystem-Atmosphere Study (BOREAS; Betts et al., 2001) and on modeling studies (e.g., Betts and Ball, 1997; Betts et al., 1996; Betts et al., 2001; Bonan, 2008; Davin and Noblet-Ducoudré, 2010; Mooney et al., 2021). These studies led to implementing more sophisticated snow sub-models in LSMs that account for the burial of vegetation by snow cover.

In the LUCAS ensemble, all LSMs, except for the TERRA-ML LSM used by CCLM-TERRA, adjust the effective Leaf and Stem Area Index for snow-buried vegetation by adopting similar approaches. Being a bulk/one-dimensional LSM, TERRA-ML applies an infinitesimal vegetation layer

https://doi.org/10.5194/tc-2021-290
Preprint. Discussion started: 18 October 2021

on top of the soil surface and has no canopy (i.e., vegetation lays flat on the surface). However, to correctly simulate the effect of trees masking the ground snow on radiation, TERRA-ML applies a reduction factor for the snow albedo when vegetation such as forest canopies masks the snow. Hence, when vegetation is snow-buried, all LSMs account for a highly reflecting surface in the calculation of surface albedo. In Table 1, interested readers may find references to RCM-dependent snow-buried vegetation schemes.

In terms of snow schemes, some LSMs contain more sophistication than others. Compared to previous CLM versions (i.e., CLM4.0 and CLM4.5), CLM5.0 used by CCLM-CLM5.0 counts more snow layers (12 instead of 5), treats separately canopy intercepted snow and more realistically captures temperature and wind effects on the density of fresh snow (Lawrence et al., 2020; van Kampenhout et al., 2017). The RCA4 model system and its internal LSM, used in RCA, include sub-grid orography in the snow cover to capture inhomogeneous snow cover in mountainous areas. Noah-MP allows for 3 snow layers, depending on the total snow depth. To provide a better representation of the ground heat fluxes, the first very layer is only 0.045 m thick. Noah-MP also considers snow interception by the canopy, accounting for wind and temperature effects on snow accumulation and precipitation from the canopy, snow melting and refreezing (Niu and Yang, 2004). The ground snow cover fraction is a function of the snow depth and density and ground roughness (Niu et al., 2007)

2.2 Reanalyses and remote sensing data

Reanalysis data from ERA5-Land (Muñoz Sabater, 2019; Muñoz Sabater et al., 2021) and MERRA-2 (Gelaro et al., 2017) as well as satellite data from the Moderate Resolution Imaging Spectroradiometer (MODIS; Hall and Riggs, 2016) are used to evaluate the modelled snow distribution and radiation in the RCMs. Specifically, we use monthly data for snow cover (variable “fractional area of land snow cover” in MERRA-2), incoming shortwave radiation from ERA5-Land and MERRA-2, and daily snow cover data from the MODIS sensors AQUA and TERRA. The reanalysis data are interpolated bilinearly to the common 0.5°x0.5° grid (see Section 2.2). Reanalysis data cover the time period 1986-2015 and MODIS data the period 2003-2015.

For MODIS data, the following processing steps are applied:

1. Data are masked according to the prevailing cloud cover since high cloud cover prevents a correct estimation of snow cover. We apply two different thresholds (20% and 50%) to the percent of clouds in each cell.
2. Only data flagged as “best”, “good”, and “ok” are used while all other data are masked.
3. Data are conservatively remapped to the common 0.5°x0.5° grid. Conservative remapping is chosen due to the large difference in resolution between the original MODIS data (0.05°) and the target grid (0.5°). It considers all grid points in the interpolation while, e.g., bilinear interpolation would only consider the neighbouring grid cells of the target grid.
4. A land-sea mask is applied to make sure that only land grid points are included in the analysis. Only grid points with more than 50% land fraction are included.

The masking for MODIS data implies that single grid points can contribute differently to the average over one region. To make the models and reanalyses comparable, each grid point is weighted by the amount of available MODIS data (individually for each month of the whole time period).

2.3 Snow Albedo Sensitivity Index (SASI) and geographical scope

SASI is an index that quantifies the climate forcing due to the snow albedo effect (Xu and Dirmeyer, 2013). It is defined as:

$$SASI = SW * \sigma(f_{sno})\Delta\alpha \qquad (1)$$

where SW is the net shortwave radiation at the surface, $\sigma(f_{sno})$ is the standard deviation of snow cover fraction, and $\Delta\alpha$ is the average difference between the albedo of a snow-covered surface and the albedo of a snow-free surface. $\Delta\alpha$ is a constant value of 0.4 as assumed in Xu and Dirmeyer (2013). SASI is in Wm^{-2} and high values of SASI, such as 10 Wm^{-2}, indicate a strong climate forcing from the snow albedo effect (Xu and Dirmeyer, 2013).

To better understand geographical differences in the role of snow for land-atmosphere coupling, we focus on three sub-regions over Europe, with different climate, vegetation cover, topography or latitudes: Scandinavia [5ºE-30ºE, 55ºN-70ºN], East Europe [16 ºE-30ºE, 44ºN-55ºN] and East Baltic [20ºE-40ºE, 50ºN-62ºN] (see Figure 1**).** The first two regions, Scandinavia and East Europe correspond

https://doi.org/10.5194/tc-2021-290
Preprint. Discussion started: 18 October 2021

to regions 8 and 5 of the PRUDENCE project (Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risk and Effects; Christensen and Christensen, 2007). The three selected regions differ in terms of climate but also in terms of vegetation: vegetation in Scandinavia is mostly trees while the two other regions are covered by cropland and trees. The Scandinavian region also stands out because of its geographical location covering high latitudes, where the incoming shortwave radiation is very small or zero during winter. In comparison with the East Baltic region, which is covered by plains, the East Europe and Scandinavia regions have a more complex topography as they encompass the Carpathian and Scandinavian mountains, respectively.

3. Results and discussion

3.1 SASI in satellite observations, reanalyses and RCMs over Europe

In Figure 2, we first show the geographical distribution of SASI over Europe based on satellite observations, the ERA5-Land reanalysis and the LUCAS models from January to June, averaged over the 1986-2015 period. Focusing first on the satellite observations and ERA5-Land, an increase in SASI can be observed during the first months of the year when solar radiation increases and snow is accumulating (accumulation period), reaching a maximum in March or April depending on the region examined, and then decreasing when snow starts melting (ablation period). At higher latitudes snow melts later than at mid-latitudes, giving rise to SASI values during spring, as shown in Figure 2. Then, SASI reaches very low values in May and June when the snow has melted almost entirely. This is as expected, and the overall seasonal trend is consistent with Xu and Dirmeyer (2013). The model data exhibits the same overall spatiotemporal cycle in SASI as the satellite observations and ERA5-Land. However, large differences can be seen between the simulations in terms of amplitude or pattern, especially during the ablation period. In March over the Carpathian Mountains, for example, SASI varies between 1 Wm^{-2} for WRFa-NoahMP and RCA, and 10 Wm^{-2} for CCLM-CLM5.0 and RegCMa-CLM4.5. It is also noteworthy that for almost all the models, SASI is close to zero everywhere in continental Europe in May and June, as the snow has almost entirely melted, while in May for RegCMb-CLM4.5 and CCLM-VEG3D there are still high values of SASI (~10 Wm^{-2}).

https://doi.org/10.5194/tc-2021-290
Preprint. Discussion started: 18 October 2021

The ensemble of simulations run for LUCAS enable us to discuss the role of different components of the RCMs, such as the land and atmosphere models or the choice in parameterizations. For example, WRFc-NoahMP and WRFa-NoahMP show noticeable differences in the amplitude and pattern of SASI (Fig. 2), even though they use the same LSM (Noah-MP) and atmospheric model (WRF). Their differences come from parameterizations (planetary boundary layer and convection), thus demonstrating the importance of atmospheric processes and their model representation for representing snow processes. Then, WRF configuration coupled with the LSM CLM4.0 (WRFb-CLM4.0) also shows different results from when it is coupled with NOAH-MP. For example, WRFa-NoahMP shows an earlier poleward migration of high SASI values compared to WRFb-CLM4.0, moving north about one month before WRFb-CLM4.0. Large differences can also be observed between CCLM-CLM5.0, CCLM-TERRA, and CCLM-VEG3D; they all use the same RCM but different LSMs. In contrast to the two other Cosmo configurations, CCLM-VEG3D uses a snow flag for snow cover (i.e., indicates if snow is present or not; Section 2.3), explaining its different representation of SASI. This suggests that SASI is very sensitive to the configurations of and process parameterizations in the climate model. In particular, the choice of the LSM or certain parameterizations (e.g. convection scheme) highly influence the representation of the climate forcing from the snow albedo effect. The role of the LSM in this context will be investigated further in the coming sections of the article.

3.2 Transition between the accumulation and ablation periods

To further investigate the differences in snow albedo coupling between the simulations and the observation-based datasets during the accumulation and ablation periods, a time-series of SASI from January to June is presented in Figure 3 for the three sub-regions East Europe, East Baltic and Scandinavia (see Figure 1 for their extents). Before looking at the differences between the different datasets, it is interesting to compare the amplitude of SASI between East Baltic and East Europe (mid-latitude regions) with Scandinavia (high-latitude region), which shows slightly higher values of SASI over the mid-latitude regions in satellite observations, ERA5 and most of the RCMs. This confirms previous findings from Xu and Dirmeyer (2013), which estimated higher values of SASI in mid- versus

https://doi.org/10.5194/tc-2021-290
Preprint. Discussion started: 18 October 2021

high-latitude regions in satellite observations. However, even with higher values at mid-latitudes, this result suggests that the radiative forcing due to the snow albedo effect is not negligible over high-latitude regions in winter and spring. This result shows again the importance of the snow-atmosphere processes in mid- and high-latitudes in the Northern hemisphere.

Then, coming back to the comparison of the different datasets, in all three regions, the models and observations indicate a pronounced peak in SASI. The maximum in SASI marks the transition between the accumulation and ablation periods. The timing of this transition depends on the region examined due to, for example, latitudinal differences in incoming solar radiation. Although the amplitude of the peak is very similar between the satellite observations and ERA5-Land, it is interesting to see that the timing differs between them, over Scandinavia and East Baltic. Over East Europe it happens in March for both the satellite observations and ERA5, for East Baltic in March (satellites) or April (ERA5) and for Scandinavia in April (satellites) or May (ERA5). The origin of these differences has not been clarified yet. This might be due to the higher elevations of these two regions compared to East Europe as complex orography is a driving factor for the spatial heterogeneity of precipitation (Grunewald et al., 2014).

The LUCAS simulations also show a pronounced peak in SASI in all regions (Fig. 3), however they do not all agree on the timing and the amplitude of the signal. For example, in the East Baltic region, some models (WRFc-NoahMP and WRFa-NoahMP) simulate a peak in March, others in April (WRFb-CLM4.0 and CCLM-CLM5.0) or even in May (RegCMb-CLM4.5 and CCLM-VEG3D). In general, RegCMb-CLM4.5 and CCLM-VEG3D tend to present the latest peak in SASI as well as the highest amplitude in the signal. On the other hand, WRFa-NoahMP tends to produce an earlier peak and lower values of SASI, especially over East Europe. These differences might be related to the way snow melts in the different models and will be further explored in the next section. More generally, we see that during the accumulation period, all the datasets are in better agreement compared to the ablation period (Fig. 3). For East Europe and East Baltic, the spread largely increases in March and for Scandinavia from April until the end of the season, when the snow is melting.

This large model spread during the ablation period is further confirmed by Figure 4 showing the pattern correlation between the simulations and ERA5-Land from January to June. For many models,

https://doi.org/10.5194/tc-2021-290
Preprint. Discussion started: 18 October 2021

the correlation is high at the beginning of the season but strongly decreases in March or April, when the snow starts melting. These results are in agreement with previous studies showing the difficulties of climate models to represent snow processes during the ablation period (Essery et al. 2009). Given the dominant role of land surface processes during the ablation period, this suggests that the choice of the LSM is more critical for the representation of the climate forcing from the snow albedo effect than the atmospheric model in spring. For calculating snow-covered areas at different stages of ablation, a correct representation of the landscape type is important (Pomeroy et al., 1998). Figure 4 also shows that the behavior of the RCMs is different between East Europe and East Baltic versus Scandinavia. Over the latter region, most RCMs differ from the reanalysis indicated by low correlations. Earlier studies showed that snow accumulates or melts very differently in an open region compared to a forested region (Jonas and Essery, 2014; Moeser et al., 2016). Our results suggest that RCMs represent snow processes better in open spaces like the East Baltic than in forest-covered regions like Scandinavia. The relationship between the representation of SASI and land cover will be further explored in the companion article, Part II. The mountains in Scandinavia could also be a source of biases since the resolution of the RCM simulations (0.44°) can be considered insufficient to represent the more complex topography of Scandinavia.

3.3 Inter-model differences in SASI

To better understand the origin of the differences in SASI across RCMs, we explore the relationship between SASI and its components, surface snow cover and shortwave radiation, during the accumulation and ablation periods. Figure 5 presents a comparison of the averaged monthly surface snow cover for the LUCAS simulations, the reanalyses MERRA-2 and ERA5-Land as well as the satellite observations from MODIS, averaged over our three regions of interest, from January to May. First, it should be noted that differences can be observed between the reanalyses and the satellite observations as the different datasets have their own limitations or biases. For example, the surface snow cover in East Baltic in March is ~0.6 for MODIS, ~0.7 for MERRA-2 and ~0.8 for ERA5-Land. It is therefore important to include several observation-based datasets to evaluate the ability of climate models to represent snow cover and estimate the uncertainties associated with this variable. The

https://doi.org/10.5194/tc-2021-290
Preprint. Discussion started: 18 October 2021

representation of snow cover in RCMs can also be different depending on the model examined. Over Scandinavia, snow cover varies between 0.4 for WRFa-NoahMP and 1.0 for WRFb-CLM4.0 in January. For the same month, the differences are even higher for the other two regions, varying between 0.3 for WRFa-NoahMP and 1.0 for WRFb-CLM4.0 in East Baltic, and 0.1 for WRFa-NoahMP and 1.0 for WRFb-CLM4.0 in East Europe. Although there are already differences during the accumulation period, Figure 5 shows that the spread increases when the snow starts melting. This result indicates a common bias between the models that highly disagree with the reanalysis and observations, regarding snow cover in spring. This confirms the result from the previous section as it is again pointing towards a bias from LSMs as this part of the RCM is primordial for representing land surface processes related to snow cover during the ablation period.

Based on Figure 3, RegCMb-CLM4.5 and CCLM-VEG3D were identified as models with higher values in SASI during the ablation period and later peaks for all regions. Figure 5 shows that this behavior can be at least partly attributed to their representation of snow cover. During the ablation period, they all tend to produce higher values of snow cover compared to the other models and also to keep high values later in the season. This behavior is confirmed by the black dots under these two models during the ablation period as they indicate when the models are outside the range of the reference datasets (MERRA-2, ERA5-Land and MODIS). This is particularly striking for CCLM-VEG3D. Similarly, the low SASI peaks for WRFa-NoahMP, which also occur earlier than the peaks for other models (Figure 3), might be related to the lower values in snow cover and the small interannual snow cover variability compared to the other RCMs, particularly in East Europe (Figure 5). Again, this is confirmed by the black dots indicated under the model. The differences in snow cover are also reflected by the rate of snow melting for the different RCMs (Supplemental Material; Figure S1). The models having high snow cover late in spring (RegCMb-CLM4.5 and CCLM-VEG3D) tend to have later snow melt than the other models while WRFa-NoahMP, showing reduced snow cover earlier than the other models, tends to melt sooner.

Another component of SASI is shortwave radiation at the surface, which is presented in Figure 6 for the LUCAS simulations, the reanalyses MERRA-2 and ERA5-Land, averaged over our three regions of interest, from January to May. The comparison between the RCMs and the reanalysis shows

https://doi.org/10.5194/tc-2021-290
Preprint. Discussion started: 18 October 2021

noticeable differences for some models. Both REMO-iMOVE and CCLM-VEG3D exhibit very different results in terms of surface shortwave radiation compared to the datasets as shown by the black dots on the figure, showing much lower and higher values, respectively. However, even with these discrepancies, they both reproduce SASI reasonably well. This seems to indicate that the differences in the representation of the forcing from the snow albedo effect are mostly driven by differences in the representation of snow cover in the models. This is confirmed by Figure 7 showing the average correlation across models between SASI and shortwave radiation (left) as well as SASI and snow cover (right) for the LUCAS models. Scandinavia and East Baltic present similar results with significant, positive correlations between SASI and snow cover for almost all months, associated with positive but not significant correlations between SASI and shortwave radiation. For East Europe, the correlation between SASI and snow cover is low and not significant in January and February but remains high and significant the rest of the time period. In parallel, the correlation between SASI and downward shortwave radiation at the surface is negative for almost all months and not significant. Overall, high and significant correlations often appear between SASI and snow cover for the three regions from January to June. On the other hand, the correlations between SASI and shortwave radiation are low and usually not significant. This indicates that the differences in the representation of the forcing from the snow albedo effect are mostly driven by differences in the representation of snow cover in the models.

4. Conclusion

Previous work already showed the difficulty for climate models to represent snow variables or processes, such as snow cover and depth (Matiu et al., 2020) or the SAF (Fletcher et al., 2015), however the origin of the differences between the models is not clear yet. In this work, we focus on the ability of RCMs to simulate the radiative forcing from the snow albedo effect in winter and spring over Europe and explore the origin of the differences between the RCMs. This forcing is represented by the index SASI, which quantifies the strength of the coupling between snow and albedo. Ten RCMs from the CORDEX Flagship Pilot Study LUCAS are compared to satellite observations and reanalysis including ERA5-Land and MERRA-2. These simulations are part of the control experiment of LUCAS, which

https://doi.org/10.5194/tc-2021-290
Preprint. Discussion started: 18 October 2021

uses the standard EURO-CORDEX domain (Jacob et al., 2014) with a horizontal grid resolution of 0.44° (around 50 km).

The results show that climate models are able to reproduce some of the SASI characteristics (e.g. existence of a peak, amplitude of the peak) compared to reanalysis and satellite observations (Section 3.1), even if large differences appear between the RCMs. The climate models' ability to represent SASI is highly related to their representation of snow cover (Section 3.3), which can be difficult to represent for climate models (Matiu et al., 2020). Our results also suggest that the models' capability highly differs between the accumulation and ablation periods. Most models have much lower agreement with reanalyses and satellite observations in the ablation period, with some exceptions (e.g. CCLM-CLM5.0 over East Europe), indicating a common bias regarding snow cover in spring, pointing towards a bias from LSMs. This bias seems to be common to most LSMs even if they are based on different assumptions and parameterizations (see Section 2.3). It is also interesting that even though CCLM-TERRA is not as advanced in terms of snow modeling compared to the other models (e.g. Section 2.1.3), it still manages to represent SASI reasonably well over Europe. In addition, the representation of the sub-grid scale surface heterogeneity (Table 1; PFT-dominant versus PFT-tile) does not seem to affect the ability of RCMs to represent snow cover or SASI.

Although it is difficult to identify the origin of the bias in the RCMs, an increase in spatial resolution might improve the simulation of snow cover and therefore the representation of SASI. For example, over Scandinavia, an increase in spatial resolution would provide a better representation of the complex topography of the region as well as its forested areas, which may lead to an improved simulation of the coupling between snow and albedo. The coming phases of LUCAS, phases 2 and 3, could help answer this question as they will produce simulations at a higher spatial resolution, 12 km and convection-permitting (<3km) respectively. Taking advantage of the different configurations of the LUCAS simulations, we have also explored the role of distinct parts of the models in their ability to represent SASI. The first part of this work has already emphasized the role of the LSMs, but other components can also play an important role. WRFc-NoahMP and WRFa-NoahMP, even though using the same RCM and LSM, show noticeable differences in the amplitude and pattern of SASI. Their differences in parameterizations (planetary boundary layer and convection) are certainly affecting the way they represent SASI, highlighting the impact of such choices and the role of atmospheric processes.

Mid- and high-latitude areas are also specifically examined looking at three sub-regions: Scandinavia, East Europe and East Baltic (Section 3.2). The comparison of the three sub-regions shows the difficulties for models to simulate SASI over Scandinavia during the accumulation and ablation periods. The simulation of snow processes in a forested region is more challenging than in an open region (Jonas and Essery, 2014; Moeser et al., 2016). Thus, potentially climate models can have more difficulties representing snow processes in forest-covered regions like Scandinavia compared to open-land regions like East Baltic. The relationship between the representation of SASI and land-cover will be further explored in the companion article (Part II), analyzing the other experiments (GRASS and FOREST) from LUCAS. Finally, the comparison of mid- versus high-latitude regions shows slightly higher values of SASI over the mid-latitude regions in satellite observations, ERA5 and most of the RCMs. This confirms previous findings from Xu and Dirmeyer (2013), which estimated higher values of SASI in mid- versus high-latitude regions in satellite observations. Our results also suggest that the climate forcing due to the snow albedo effect is not negligible over high-latitude regions in winter and spring. This is important since often the land-atmosphere coupling is considered weaker at higher latitudes (Xu and Dirmeyer, 2011) but it is also possible that this coupling happens through snow and is therefore underestimated.

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References:

Beniston, M., Farinotti, D., Stoffel, M., Andreassen, L.M., Coppola, E., Eckert, N., Fantini, A., Giacona, F., Hauck, C., Huss, M., Huwald, H., Lehning, M., López-Moreno, J.I., Magnusson, J., Marty, C., Morán-Tejéda, E., Morin, S., Naaim, M., Provenzale, A., Rabatel, A., Six, D., Stötter, J., Strasser, U., Terzago, S., Vincent, C., The European mountain cryosphere: A review of its current state, trends, and future challenges, Cryosphere, 12 (2), pp. 759-794, 2018.

Betts, A. K., Ball, J. H., Beljaars A. C. M., Miller, M. J. and Viterbo, P. A.: The land surface-atmosphere interaction: A review based on observational and global modeling perspectives, Journal of Geophysical Research: Atmospheres. 101(D3), 7209-7225, 10.1029/95jd02135, 1996.

https://doi.org/10.5194/tc-2021-290
Preprint. Discussion started: 18 October 2021

Betts, A. K. & Ball, J. H.: Albedo over the boreal forest, Journal of Geophysical Research: Atmospheres. 102(D24), 28901-28909, 10.1029/96jd03876, 1997.

Betts, A. K., Ball, J. H. and McCaughey, J. H.: Near-surface climate in the boreal forest, Journal of Geophysical Research: Atmospheres. 106(D24), 33529-33541, 10.1029/2001jd900047, 2001.

Bonan, G. B.: Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests, Science. 320(5882), 1444-1449, 10.1126/science.1155121, 2008.

Braun, F. J., & Schädler G.: Comparison of soil hydraulic parameterizations for mesoscale meteorological models. *Journal of Applied Meteorology*, *44*(7), 1116-1132, 2005.

Breil, M., & Schädler, G.: Quantification of the uncertainties in soil and vegetation parameterizations for regional climate simulations in Europe. Journal of Hydrometeorology, 18(5), 1535-1548, 2017.

Breil, M., Rechid, D., Davin, E, de Noblet-Ducoudré, N., Katragou, E., Cardoso, R., Hoffmann P., Jach, L., Soares, P., Sofiadis, G., Strada, S., Strandberg, G., Toelle, M., Warrach-Sag, K.: The opposing effects of afforestation on the diurnal temperature cycle at the surface and in the atmospheric surface layer in the European summer. *Journal of Climate*, 33 (21), pp. 9159-9179, 2020.

C3S: Copernicus Climate Change Service (C3S) (2017): ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate . Copernicus Climate Change Service Climate Data Store (CDS), date of access 200414. https://cds.climate.copernicus.eu/cdsapp#!/home, 2017.

Christensen, J.H., and Christensen, O.B.: A summary of the PRUDENCE model projections of changes in European climate by the end of this century. *Climatic Change* 81, 7–30,. https://doi.org/10.1007/s10584-006-9210-7, 2007.

Davin, E. L., & Noblet-Ducoudré, N. D.: Climatic Impact of Global-Scale Deforestation: Radiative versus Nonradiative Processes, Journal of Climate. 23(1), 97-112, 10.1175/2009jcli3102.1, 2010.

Davin, E. L., Rechid, D., Breil, M., Cardoso, R. M., Coppola, E., Hoffmann, P., Jach, L. L., Katragkou, E., de Noblet-Ducoudré, N., Radtke, K., Raffa, M., Soares, P. M. M., Sofiadis, G., Strada, S., Strandberg, G., Tölle, M. H., Warrach-Sagi, K. & Wulfmeyer, V.: Biogeophysical impacts of forestation in Europe: first results from the LUCAS (Land Use and Climate Across Scales) regional climate model intercomparison, Earth Syst. Dynam. 11(1), 183-200, 10.5194/esd-11-183-2020, 2020.

Deardorff, J.: Efficient prediction of ground surface temperature and moisture, with inclusion of a layer of vegetation, J. Geophys. Res, 83(4), 1889 –1903, doi:10.1029/JC083iC04p01889, 1978.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N., & Vitart, F.: The ERA-Interim reanalysis: configuration and performance of the data assimilation system, Quarterly Journal of the Royal Meteorological Society. 137(656), 553-597, 10.1002/qj.828, 2011.

Diro, G. T., & Sushama, L.: Snow–precipitation coupling and related atmospheric feedbacks over North America, Atmospheric Science Letters. 19(8), e831, 10.1002/asl.831, 2018.

Doms, G., Förstner, J., Heise, E., Herzog, H.-J., Mironov, D., Raschendorfer, M., Reinhardt, T., Ritter, Schrodin, B.R., Schulz, J.-P., Vogel G.: A Description of the Nonhydrostatic Regional Model LM, Part II: Physical Parameterization. DWD, 2013.

Essery, R., and Coauthors, 2009: SNOWMIP2: An Evaluation of Forest Snow Process Simulations. *Bull. Amer. Meteor. Soc.*, **90**, 1120–1136, https://doi.org/10.1175/2009BAMS2629.1.

Fletcher, C. G., Thackeray, C. W., and Burgers, T. M.: Evaluating biases in simulated snow albedo feedback in two generations of climate models, *J. Geophys. Res. Atmos.*, 120, 12– 26, doi:10.1002/2014JD022546, 2015.

Gelaro R., McCarty W., Suárez M. J., Todling R., Molod A., Takacs L., Randles C. A., Darmenov A., Bosilovich M. G., Reichle R., Wargan K., Coy L., Cullather R., Draper C., Akella S., Buchard V., Conaty A., Silva A. M. d., Gu W., Kim G.-K., Koster R., Lucchesi R., Merkova D., Nielsen J. E., Partyka G., Pawson S., Putman W., Rienecker M., Schubert S. D., Sienkiewicz M. & Zhao B.: The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2), Journal of Climate. 30(14), 5419-5454, 10.1175/jcli-d-16-0758.1, 2017.

https://doi.org/10.5194/tc-2021-290
Preprint. Discussion started: 18 October 2021

Giorgi F., Coppola, E., Solmon, F., Mariotti, L., Sylla, M.B., Bi, X., Elguindi, N., Diro, G.T., Nair, V., Giuliani, G., Turuncoglu, U.U., Cozzini, S., Güttler, I., O'Brien, T.A., Shalaby A. Tawfik, A. B., Zakey, A.S., Steiner, A.L., Stordal, F., Sloan, L.C., & Brankovic C.: RegCM4: model description and preliminary tests over multiple CORDEX domains. Clim. Res., 52:7–29. doi: 10.3354/cr01018, 2012.

Grabe, F.: Simulation der Wechselwirkung zwischen Atmosphäre, Vegetation und Erdoberfläche bei Verwendung unterschiedlicher Parametrisierungsansätze. PhD Thesis. Inst. for Meteorology and Climate Research, Karlsruhe Institute of Technology, Karlsruhe, Germany, 2002.

Grünewald, T., Bühler, Y., and Lehning, M.: Elevation dependency of mountain snow depth, The Cryosphere, 8, 2381–2394, https://doi.org/10.5194/tc-8-2381-2014, 2014.

Gobiet, A., Kotlarski, S., Beniston, M., Heinrich, G., Rajczak, J., Stoffel, M.: 21st century climate change in the European Alps—A review. Science of the Total Environment 493, 1138–1151, 2014.

Henderson, G. R., Peings, Y., Furtado, J. C. & Kushner, P. J.: Snow–atmosphere coupling in the Northern Hemisphere, Nature Climate Change. 8(11), 954-963, 10.1038/s41558-018-0295-6, 2018.

Hall, D. K. and Riggs, G.A.: MODIS/Terra Snow Cover Daily L3 Global 0.05Deg CMG, Version 6. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. doi: https://doi.org/10.5067/MODIS/MOD10C1.006. (accessed on 15.08.2020), 2016.

Jacob, D., and Coauthors: Assessing the transferability of the regional climate model REMO to different CORDEX regions, *Atmosphere*, 3, 181-199, DOI:10.3390/atmos3010181, 2012.

Jonas, T., and Essery R.: Snow Cover and Snowmelt in Forest Regions. In: Singh V.P., Singh P., Haritashya U.K. (eds) Encyclopedia of Snow, Ice and Glaciers. Encyclopedia of Earth Sciences Series. Springer, Dordrecht. https://doi.org/10.1007/978-90-481-2642-2_499, 2014.

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O. B., Bouwer, L. M., Braun, A., Colette, A., Déqué, M., Georgievski, G., Georgopoulou, E., Gobiet, A., Menut, L., Nikulin, G., Haensler, A., Hempelmann, N., Jones, C., Keuler, K., Kovats, S., Kröner, N., Kotlarski, S., Kriegsmann, A., Martin, E., van Meijgaard, E., Moseley, C., Pfeifer, S., Preuschmann, S., Radermacher, C., Radtke, K., Rechid, D., Rounsevell, M., Samuelsson, P., Somot, S., Soussana, J.-F., Teichmann, C., Valentini, R.,

https://doi.org/10.5194/tc-2021-290
Preprint. Discussion started: 18 October 2021

Vautard, R., Weber, B. & Yiou, P.: EURO-CORDEX: new high-resolution climate change projections for European impact research, Regional Environmental Change. 14(2), 563-578, 10.1007/s10113-013-0499-2, 2014.

Jacob, D., Teichmann, C., Sobolowski, S. et al.*:* Regional climate downscaling over Europe: perspectives from the EURO-CORDEX community. *Reg Environ Change* **20,** 51. https://doi.org/10.1007/s10113-020-01606-9, 2020.

Kotlarski, S.: A Subgrid Glacier Parameterisation for Use in Regional Climate Modelling, Max-Planck Institut für Meteorologie Report No. **, 2007.

Lawrence, D. & Coauthors: Technical Description of version 5.0 of the Community Land Model (CLM), Boulder, CO, 329 pp, 2020.

Lüthi, S,. Ban, N., Kotlarski, S., Steger, C.R., Jonas, T., Schär, C.: Projections of Alpine Snow-Cover in a High-Resolution Climate Simulation. *Atmosphere*.; 10(8):463. https://doi.org/10.3390/atmos10080463, 2019.

Magnusson, J., Tobias, J., López-Moreno, I., Lehning, M.; Snow cover response to climate change in a high alpine and half-glacierized basin in Switzerland. *Hydrology Research*; 41 (3-4): 230–240. doi: https://doi.org/10.2166/nh.2010.115, 2010.

Matiu, M., Petitta, M., Notarnicola, C., Zebisch, M. Evaluating Snow in EURO-CORDEX Regional Climate Models with Observations for the European Alps: Biases and Their Relationship to Orography, Temperature, and Precipitation Mismatches. *Atmosphere*. 11(1):46. https://doi.org/10.3390/atmos11010046, 2020.

Matiu, M., Crespi, A., Bertoldi, G., Carmagnola, C. M., Marty, C., Morin, S., Schöner, W., Cat Berro, D., Chiogna, G., De Gregorio, L., Kotlarski, S., Majone, B., Resch, G., Terzago, S., Valt, M., Beozzo, W., Cianfarra, P., Gouttevin, I., Marcolini, G., Notarnicola, C., Petitta, M., Scherrer, S. C., Strasser, U., Winkler, M., Zebisch, M., Cicogna, A., Cremonini, R., Debernardi, A., Faletto, M., Gaddo, M., Giovannini, L., Mercalli, L., Soubeyroux, J.-M., Sušnik, A., Trenti, A., Urbani, S., and Weilguni, V.: Observed snow depth trends in the European Alps: 1971 to 2019, The Cryosphere, 15, 1343–1382, https://doi.org/10.5194/tc-15-1343-2021, 2021.

https://doi.org/10.5194/tc-2021-290
Preprint. Discussion started: 18 October 2021

Mioduszewski, J.R., Rennermalm, A.K., Robinson, D.A., Wang, L. Controls on spatial and temporal variability in Northern Hemisphere terrestrial snowmelt timing, 1979-2012. Journal of Climate, 28 (6), pp. 2136-2153, 2015.

Moeser, D., Mazzotti, G., Helbig, N., and Jonas, T.: Representing spatial variability of forest snow: Implementation of a new interception model, *Water Resour. Res.*, 52, 1208– 1226, doi:10.1002/2015WR017961, 2016.

Mooney, P. A., Lee, H., and Sobolowski, S.: Impact of quasi-idealized future land cover scenarios at high latitudes in complex terrain. Earth's Future, 9 (2), e2020EF001838. https://doi.org/10.1029/2020EF001838, 2021.

Muñoz Sabater, J.: ERA5-Land monthly averaged data from 1981 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). (accessed on 31.08.2020), 10.24381/cds.68d2bb30, 2019.

Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., Boussetta, S., Choulga, M., Harrigan, S., Hersbach, H., Martens, B., Miralles, D. G., Piles, M., Rodríguez-Fernández, N. J., Zsoter, E., Buontempo, C., and Thépaut, J.-N.: ERA5-Land: A state-of-the-art global reanalysis dataset for land applications, Earth Syst. Sci. Data Discuss. [preprint], https://doi.org/10.5194/essd-2021-82, in review, 2021.

Niu, G.-Y., and Yang, Z.L.: The effects of canopy processes on snow surface energy and mass balances, J. Geophys. Res., 109, D23111, doi:10.1029/2004JD004884, 2004.

Niu, G.-Y., and Z.-L. Yang: An observation-based formulation of snow cover fraction and its evaluation over large North American river basins, J. Geophys. Res., 112, D21101, doi:10.1029/2007JD008674, 2007.

Niu, G. Y., & Coauthors: The community Noah land surface model with multiparameterization options (Noah-MP): 1. Model description and evaluation with local-scale measurements. *Journal of Geophysical Research: Atmospheres*, *116*(D12), 2011.

Oleson, K. W., Lawrence, D. M., Bonan, G. B., Flanner, M. G., Kluzek, E., Lawrence, P. J., … Zeng, X.: Technical Description of version 4.0 of the Community Land Model (CLM) (No. NCAR/TN-478+STR). University Corporation for Atmospheric Research. doi:10.5065/D6FB50WZ, 2010.

https://doi.org/10.5194/tc-2021-290
Preprint. Discussion started: 18 October 2021

Oleson K. W. & Coauthors: Technical description of version 4.5 of the Community Land Model (CLM). Boulder, CO, 420 pp, 2013.

Pomeroy, J.W., Gray, D.M., Shook, K.R., Toth, B., Essery, R.L.H., Pietroniro, A. and Hedstrom, N.: An evaluation of snow accumulation and ablation processes for land surface modelling. Hydrol. Process., 12: 2339-2367. https://doi.org/10.1002/(SICI)1099-1085(199812)12:15<2339::AID-HYP800>3.0.CO;2-L, 1998.

Thackeray, C.W., Qu, X. and Hall, A.: Why do models produce spread in snow albedo feedback?. Geophysical Research Letters, 45(12), pp.6223-6231, 2018.

Qu, X., and A. Hall: What Controls the Strength of Snow-Albedo Feedback?. *J. Climate*, **20**, 3971–3981, https://doi.org/10.1175/JCLI4186.1, 2007.

Qu X. and A. Hall: On the persistent spread in snow-albedo feedback. Clim Dyn, 42:69–81 DOI:10.1007/s00382-013-1774-0, 2014.

Reinhart V., Fonte C., Hoffmann P., Bechtel B., Rechid D., Böhner J.: Comparison of ESA Climate Change Initiative Land Cover to CORINE Land Cover over Eastern Europe and the Baltic States from a regional climate modeling perspective. Int. J. Earth Obs. 94, 102221. https://doi.org/10.1016/j.jag.2020.102221, 2020.

Rechid, D., Davin, E., de Noblet-Ducoudré, N., and Katragkou, E.: CORDEX Flagship Pilot Study LUCAS – Land Use & Climate Across Scales – a new initiative on coordinated regional land use change and climate experiments for Europe, in 19th EGU General Assembly, EGU2017, proceedings from the conference held 23–28 April, 2017 in Vienna, Austria, 19, p. 13172, 2017.

Rockel B., Will A. & Hense A.: The regional climate model COSMO-CLM (CCLM). *Meteorologische Zeitschrift*, *17*(4), 347-348, 2008.

Roeckner E., Arpe K., Bentsson L., Christoph M., Claussen M., Dümenil L., Esch M., Giorgetta M., Schlese U. & Schulzweida U.: The atmospheric general circulation model ECHAM-4: Model description and simulation of present day climate. Max-Planck Institut für Meteorologie Report No. 218, 90 pp. , 1996.

https://doi.org/10.5194/tc-2021-290
Preprint. Discussion started: 18 October 2021

Samuelsson, P., Gollvik S., Jansson, C., Kupiainen, M., Kourzeneva, E., & Jan van de Berg, W.: The surface processes of the Rossby Centre regional atmospheric climate model (RCA4). Reports METEOROLOGY, 157, SMHI, Norrköping, Sweden, 2015.

Samuelsson, P., Gollvik, S., & Ullerstig, A.: The land-surface scheme of the Rossby Centre regional atmospheric model (RCA3). Reports Meteorology, 122, SMHI, SE-60176 Norrköping, Sweden, 2006.

Schrodin, E., and Heise, E.:A new multi-layer soil model. COSMO Newsletter No. 2:149-151, 2002.

Skamarock, W. C., and Coauthors: A description of the advanced research WRF version 3, NCAR Technical Note. *National Center for Atmospheric Research, Boulder, Colorado*, USA, 2008.

Sofiadis, G., Katragkou, E., Davin, E. L., Rechid, D., de Noblet-Ducoudre, N., Breil, M., Cardoso, R. M., Hoffmann, P., Jach, L., Meier, R., Mooney, P., Soares, P. M. M., Strada, S., Tolle, M. H., and Warrach Sagi, K.: Afforestation impact on soil temperature in regional climate model simulations over Europe, Geosci. Model Dev. Discuss. [preprint], https://doi.org/10.5194/gmd-2021-69, in review, 2021.

Strandberg, G., Bärring L., Hansson U., Jansson C., Jones C., Kjellström E., Kolax M., Kupiainen M., Nikulin G., Samuelsson P., Ullerstig A. & Wang S.: CORDEX scenarios for Europe from the Rossby Centre regional climate model RCA4. SMHI Meteorology and Climatology Rep. 116, 84 pp., https://www.smhi.se/polopoly_fs/1.90275!/Menu/general/extGroup/attachmentColHold/mainCol1/file/RMK_116.pdf, 2015.

Sørland, S. L., Brogli, R., Pothapakula, P. K., Russo, E., Van de Walle, J., Ahrens, B., Anders, I., Bucchignani, E., Davin, E. L., Demory, M.-E., Dosio, A., Feldmann, H., Früh, B., Geyer, B., Keuler, K., Lee, D., Li, D., van Lipzig, N. P. M., Min, S.-K., Paniz, H.-J., Rockel, B., Schär, C., Steger, C., and Thiery, W.: COSMO-CLM Regional Climate Simulations in the CORDEX framework: a review, Geosci. Model Dev. Discuss. [preprint], https://doi.org/10.5194/gmd-2020-443, in review, 2021.

van Kampenhout, L., J.T.M. Lenaerts, W.H. Lipscomb, W.J. Sacks, D.M. Lawrence, A.G. Slater & M.R. van den Broeke: Improving the Representation of Polar Snow and Firn in the Community Earth

https://doi.org/10.5194/tc-2021-290
Preprint. Discussion started: 18 October 2021

System Model. Journalof Advances in Modeling Earth Systems 9, no. 7: 2583–2600. https://doi.org/10.1002/2017MS000988, 2017.

Wang A. & Zeng X.: Improving the treatment of the vertical snow burial fraction over short vegetation in the NCAR CLM3, Advances in Atmospheric Sciences. 26(5), 877-886, 10.1007/s00376-009-8098-3, 2009.

Wilhelm C., Rechid D. & D. Jacob: Interactive coupling of regional atmosphere with biosphere in the new generation regional climate system model REMO-iMOVE. *Geoscientific Model Development*, *7*(3), 1093-1114, 2014.

Xu, L., & Dirmeyer, P.: Snow–Atmosphere Coupling Strength. Part I: Effect of Model Biases, Journal of Hydrometeorology. 14(2), 389-403, 10.1175/jhm-d-11-0102.1, 2013.

Xu, L., and Dirmeyer, P.: Snow-atmosphere coupling strength in a global atmospheric model, *Geophys. Res. Lett.*, 38, L13401, doi:10.1029/2011GL048049, 2011.

Ye, H. and Cohen, J.: A shorter snowfall season associated with higher air temperatures over northern Eurasia, Environmental Research Letters, 8, 014052, doi:10.1088/1748-9326/8/1/014052, 2013.

https://doi.org/10.5194/tc-2021-290
Preprint. Discussion started: 18 October 2021

Figures and Tables

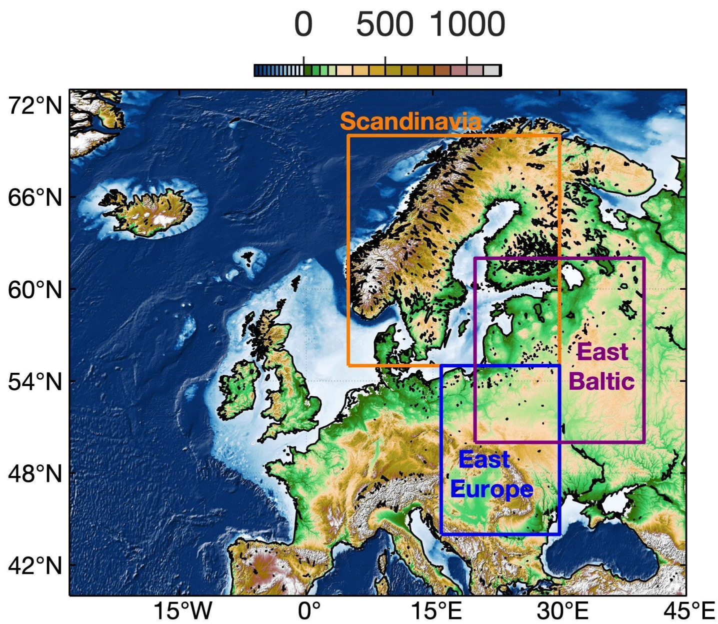
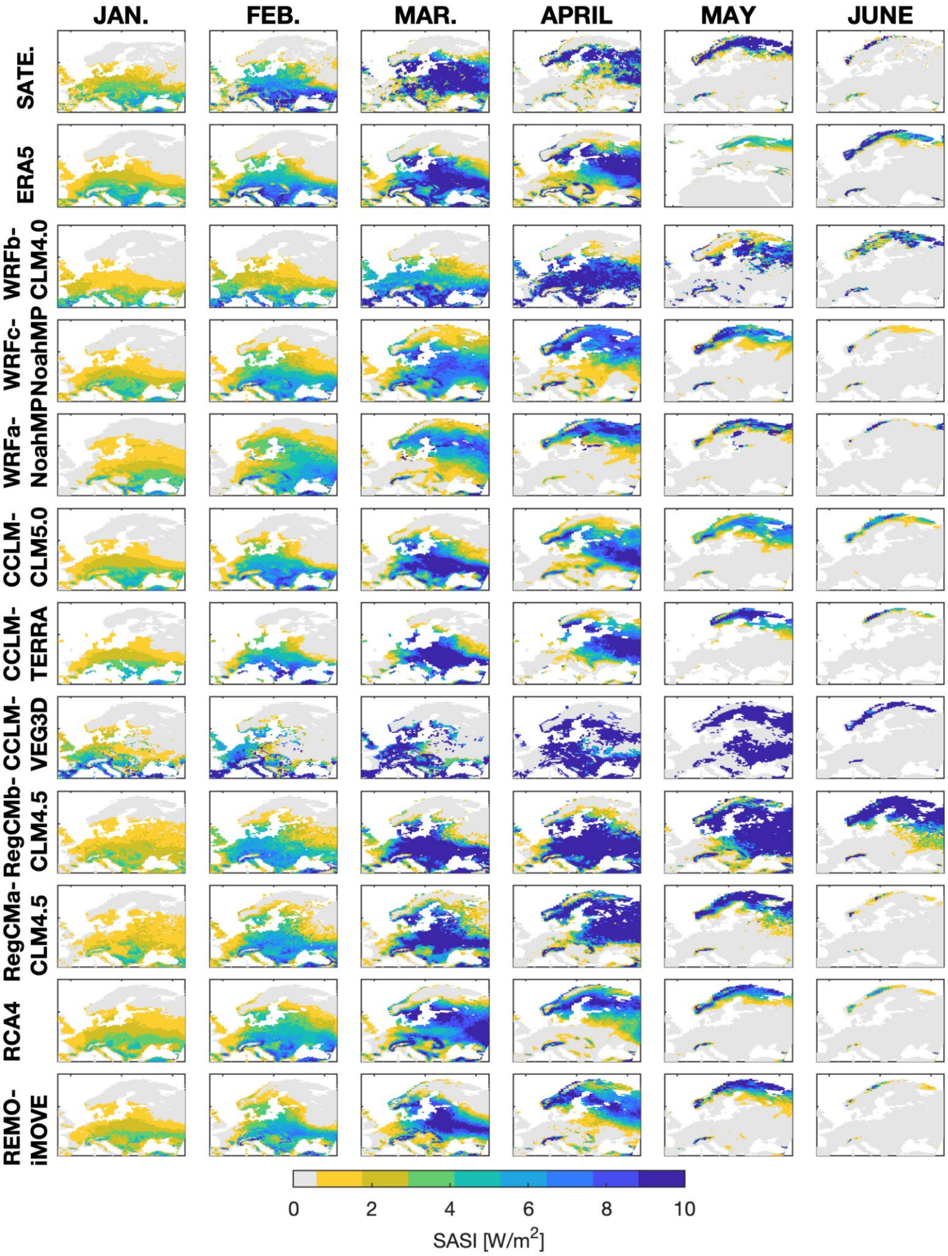


Figure 1: Map showing the location of the three regions of interest: Scandinavia (red), East Baltic (pink) and East Europe (blue).

https://doi.org/10.5194/tc-2021-290
Preprint. Discussion started: 18 October 2021



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674 **Figure 2:** Spatial maps of SASI (Wm^{-2}) for satellite observations, the reanalysis ERA5-Land and the
675 ten regional climate simulations from the EVAL experiment of LUCAS from January to June, averaged
676 over the time period 1986-2015.

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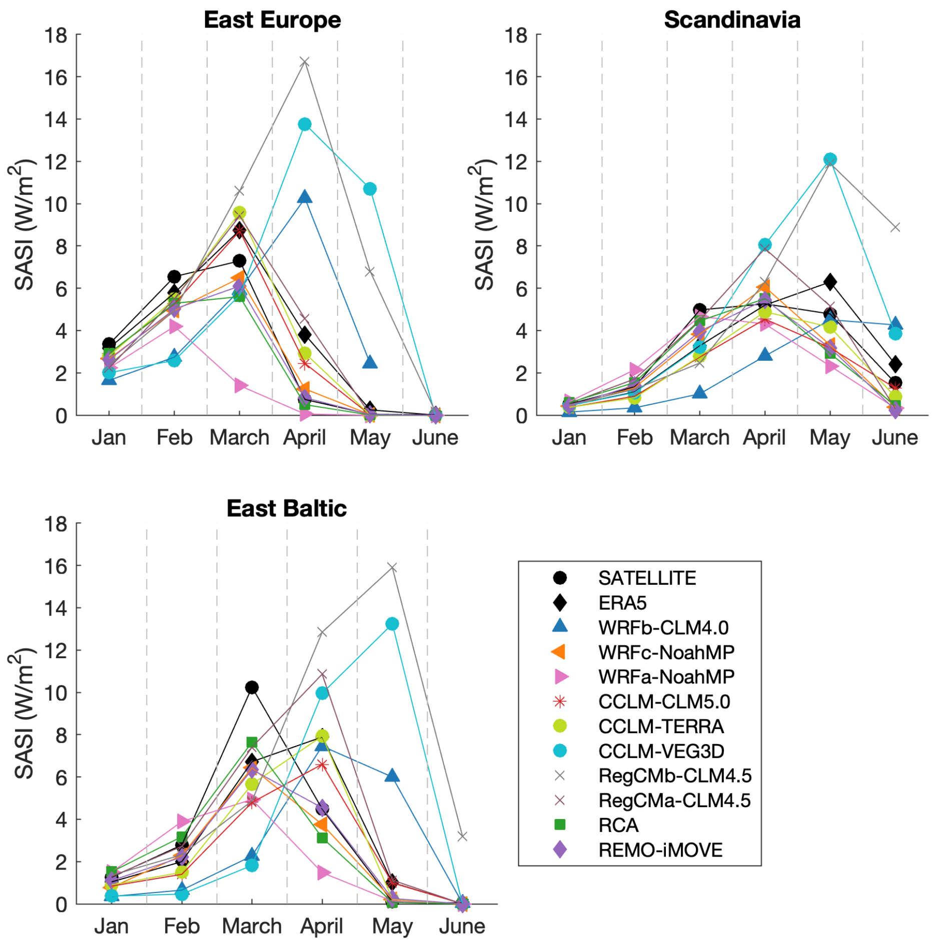

Figure 3: Time series of the spatial average of SASI for the satellite observations, the reanalysis ERA5-Land and the ten regional climate simulations from the EVAL experiment of LUCAS in Scandinavia, East Europe and East Baltic (see Figure 1 for their spatial extent). Data are averaged over the time period 1986-2015.

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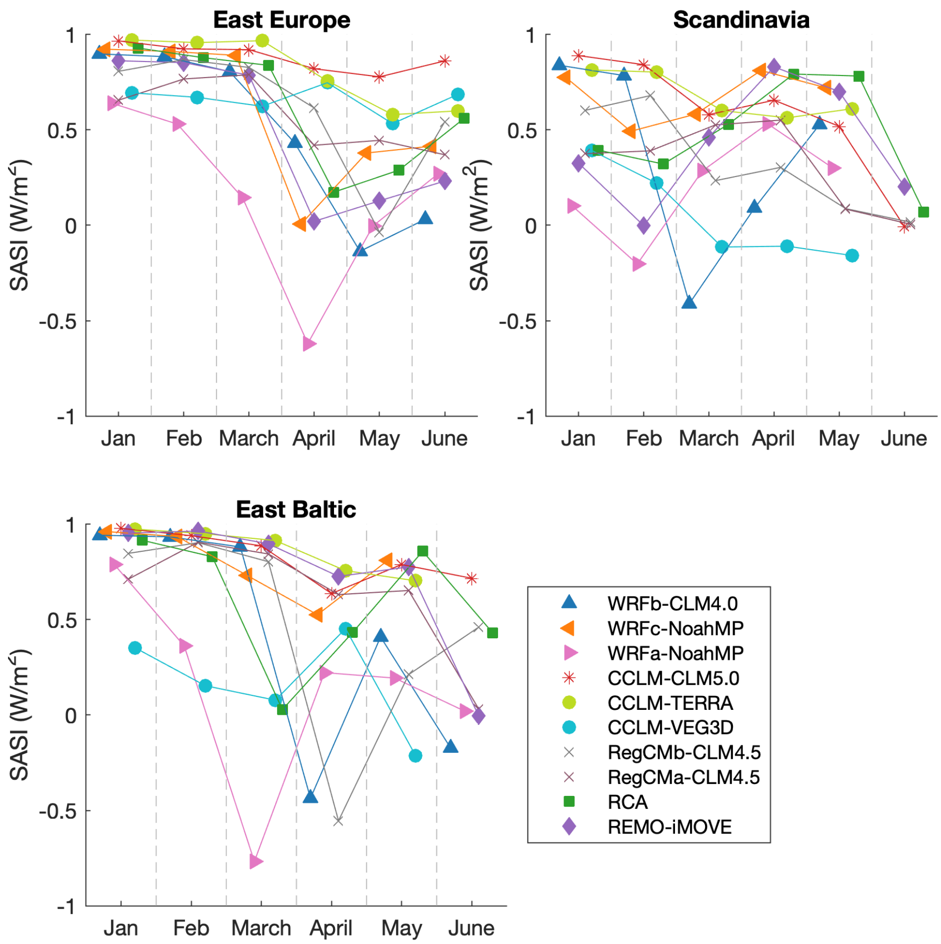

Figure 4: As in Figure 3 but for the pattern correlation between SASI and ERA5-Land for the LUCAS simulations.

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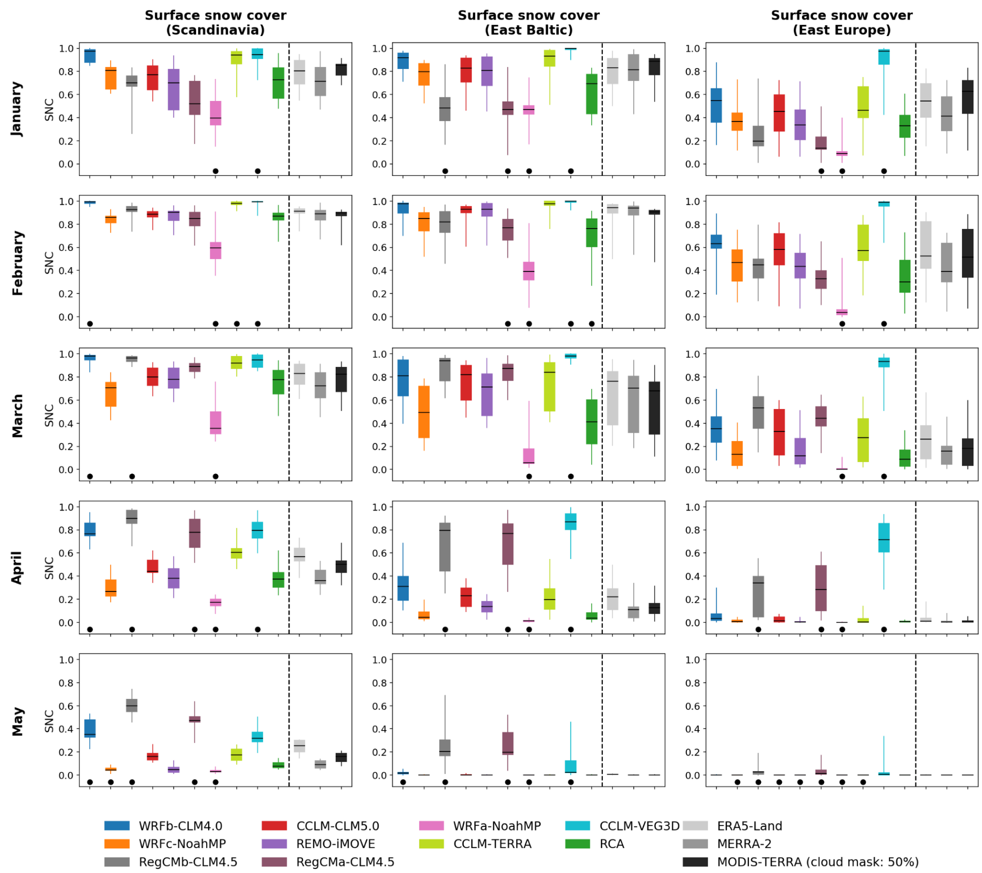

Figure 5: Snow cover for the 10 RCMs, MERRA-2, ERA5-Land, and MODIS satellite observations (using only data from days and pixels with less than 50% cloud cover) for January to May. The box-and-whisker-plots show the interannual variability of snow cover over 1986-2015, with the bar representing the median, boxes the interquartile range, and whiskers the minimum/maximum values. Dots indicate models lying outside the range of the reference datasets MERRA-2, ERA5-Land, and MODIS (i.e., the 25th (75th) model percentile is higher (lower) than the highest 75th (lowest 25th) quantile of the reference datasets).

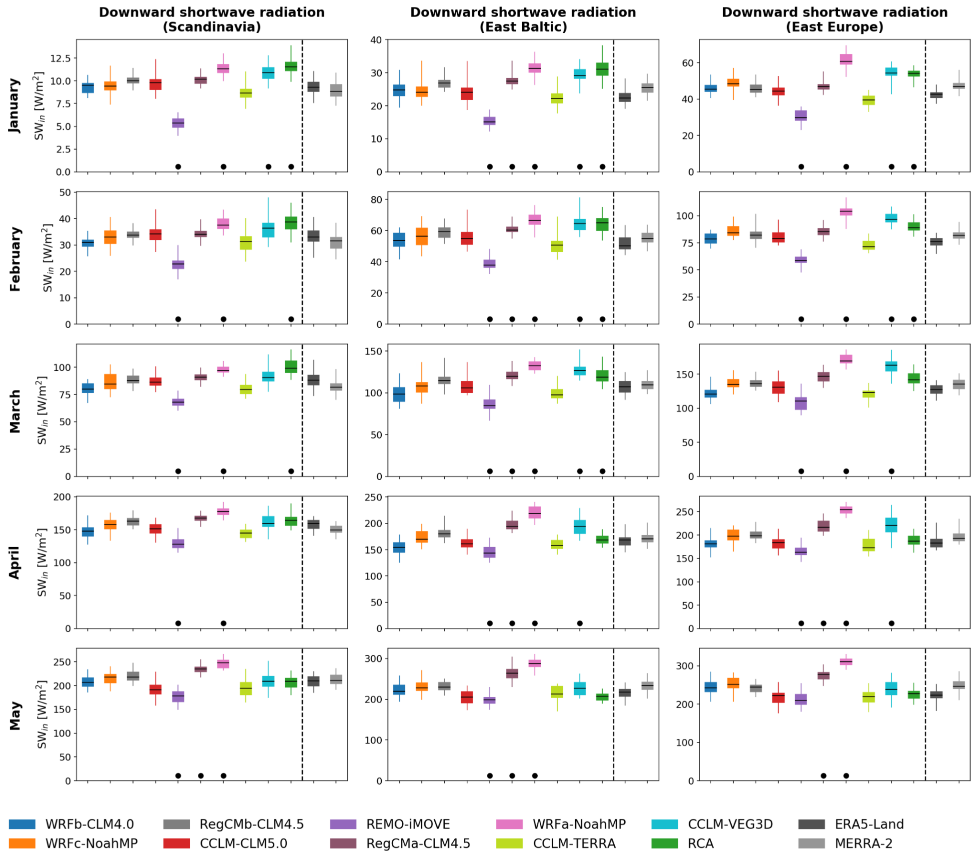

Figure 6: Downward surface shortwave radiation for the 10 RCMs for MERRA-2, and ERA5-Land, for January to May. The box-and-whisker-plots show the interannual variability of downward shortwave radiation over 1986-2015, with the bar representing the median, boxes the interquartile range, and whiskers the minimum/maximum values. Dots indicate models lying outside the range of the reference datasets MERRA-2, ERA5-Land, and MODIS (i.e., the 25th (75th) model percentile is higher (lower) than the highest 75th (lowest 25th) quantile of the reference datasets).

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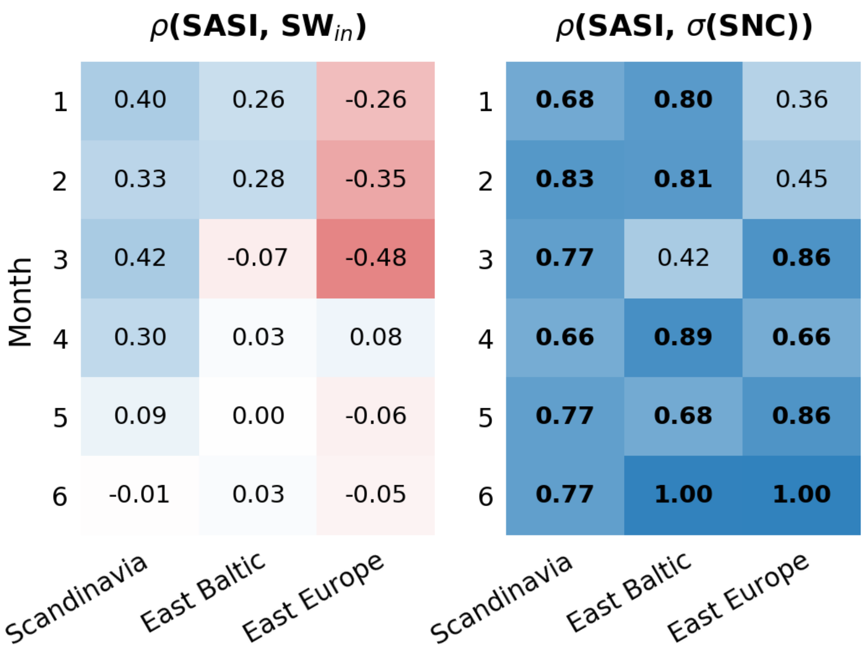

Figure 7: Pearson correlation between SASI and shortwave radiation (left), and SASI and standard deviation of snow cover (right) calculated across RCMs for the three regions Scandinavia, East Baltic, and East Europe for the months January to June during 1986-2015. The values represent the variable (shortwave radiation or variability in snow cover) to which the inter-model variability of SASI is predominantly related to. Bold values indicate statistical significance at the 0.05 level (two-tailed p-value).

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Institute ID	RCM	LSM	Representation of sub-grid scale surface heterogeneity	Phenology	Snow- vegetation interaction	Name of the models
BCCR	WRF v3.8.1 [Skamarock et al., 2008]	NoahMP [Niu et al., 2011]	PFT-dominant	Prescribed	Deardorff, 1978; Niu and Yang, 2007	WRFc-NoahMP
CUNI	RegCM v4.7 [Giorgi et al., 2012]	CLM4.5 [Oleson et al., 2013]	PFT-tile	Prescribed	Wang and Zeng, 2009	RegCMb-CLM4.5
ETH	Cosmo_5.0_clm9 [Soerland et al., 2021]	CLM5.0 [Lawrence et al., 2020]	PFT-tile	Prescribed	Wang and Zeng, 2009; Lawrence et al., 2020; van Kampenhout et al., 2017	CCLM-CLM5.0
GERICS	REMO2009 [Jacob et al., 2012]	iMOVE [Wilhelm et al., 2014]	PFT-tile	Interactive	Roeckner et al., 1996; Kotlarski, 2007	REMO-iMOVE
ICTP	RegCM v4.6 [Giorgi et al., 2012]	CLM4.5 [Oleson et al., 2013]	PFT-tile	Prescribed	Wang and Zeng, 2009	RegCMa-CLM4.5
IDL	WRF v3.8.1D [Skamarock et al., 2008]	NoahMP [Niu et al., 2011]	PFT-dominant	Prescribed	Deardorff, 1978; Niu and Yang, 2007	WRFa-NoahMP
KIT	Cosmo_5.0_clm9 [Soerland et al., 2021; Rockel et al., 2008]	VEG3D [Braun and Schädler, 2005]	PFT-dominant	Prescribed	Grabe, 2002	CCLM-VEG3D
SMHI	RCA4 [Strandberg et al., 2015]	Internal [Samuelsson et al., 2006]	PFT-tile	Prescribed	Samuelsson et al., 2015	RCA
AUTH	WRF v3.8.1 [Skamarock et al., 2008]	CLM4.0 [Oleson et al., 2010]	PFT-tile	Prescribed	Wang and Zeng, 2009	WRFb-CLM4.0
CLMcom-JLU	Cosmo_5.0_clm9 [Soerland et al., 2021]	TERRA-ML [Schrodin and Heise, 2002]	PFT-dominant	Prescribed	Doms et al., 2013	CCLM-TERRA

Table 1: Summary of participating RCMs and their LSMs.