We wish to thank the anonymous reviewers for their comprehensive and constructive comments. Below, we provide detailed responses and describe the corresponding changes in the manuscript.

Referee #1

The study by Davin et al. seeks to understand the impact of vegetation cover across Europe, using multiple terrestrial biosphere models coupled with regional atmospheric models. To test the sensitivity of the coupled models, they carried out theoretical simulations using minimum (i.e. grassland) and maximum forest cover in the domain. The authors found that, except for a few consistent changes, such as increase in albedo in the grassland simulations, the response of the models diverged considerably, and seemed to be more related to differences amongst the terrestrial biosphere models than the atmospheric model. This study provides an interesting insight of the drivers of divergent responses of coupled models to the same scenarios, and has a potential of becoming an important contribution to our understanding of biosphere-atmosphere interactions at regional scales. However, I think the manuscript needs some improvement and further development in the analysis and the interpretation of the results before it can be published.

First, the current analysis is a bit thin in assessing how atmospheric changes caused by the land cover scenarios are driving the near-surface variability across models. The authors briefly discuss these effects as potentially important, but this could be much more developed and quantified, considering that the authors are using coupled models. Just to cite one example, in the fraction of unexplained variance analysis (Fig. 10), the authors found that albedo and evaporative fraction show little explanatory power during the winter in Scandinavia. I think it should be straightforward to include some atmospheric variables such as cloud cover or incoming radiation, rainfall, or precipitable water as additional predictors. This analysis could help to quantify how surface and indirect atmospheric processes modulate surface temperature, and how this varies across regions and season.

Response: Thank you for this suggestion. It is correct that our findings suggest that atmospheric feedbacks are more important during winter and we agree that extending our correlation analysis to atmospheric variables could help demonstrating this point more directly. Note also that this study is meant to present a first overview of the LUCAS phase 1 results focusing on temperature and energy balance at seasonal timescales (as stated in the introduction) and will be complemented by further studies analyzing more specific aspects (in particular one study investigating the role of atmospheric processes in more details is planned).

Changes to manuscript: We added incoming radiation in our correlation analysis (Fig. 12; we also switched to using 2-meter temperature in this analysis for consistency with the rest of the paper). This shows that this variable (capturing in particular possible cloud feedbacks) is able to explain some additional variance including in winter although an important part of the variance still remains unexplained in winter (which also shows the limit of this kind of simple linear regression analysis). Also we moved the shortwave radiation figures into the main text to support the discussion of radiation changes.

In addition, as the authors noted in the text (Line 96), some combinations of models differ by only a few specific parametrisations. I think the authors could provide more insights on how the model settings and parameters are driving the differences in simulations. For example, between WRFa-NoahMP and WRFb-NoahMP simulations, the only relevant differences are the spin-up period and the sub-grid convection scheme, yet the results for precipitation in the summer are quite different (e.g Fig. 12). In *this case, a brief discussion on how Grell and Freitas (2014) and Kain and Fritsch (1990) differ and how the changes in surface could impact the precipitation response given the assumptions of these schemes would be very informative. Likewise, the authors included CCLM simulations with three different land surface models and a similar discussion could be included.*

Response: The main advantage of presenting results from both WRFa-NoahMP and WRFb-NoahMP is that we can clearly attribute differences in simulated response to atmospheric processes (because the same LSM is used in both configurations). However, it is really challenging to attribute differences to specific atmospheric processes because the atmospheric schemes differ in several aspects (most notably convection and microphysics). As an example, the Kain-Fritsch scheme uses a mass flux approach which rearranges each column's mass in order to remove at least 90% of the convective available potential energy (CAPE). KF is highly influenced by the boundary layer forcing, particularly surface convergence (Gallus, 1999 and Liang et al., 2004b). The Grell-Freitas scheme is based on a scale-aware method with a large-scale instability tendency closure and is more sensitive to large-scale vertical motion than the KF scheme (Dai et al., 1999). Overall, the GF scheme is known to be usually drier than the KF scheme (Hu et al., 2018). In this light, it is well possible that the slight summer precipitation decrease in WRFa-NoahMP is related to the use of the GF scheme (while precipitation is less clearly affected in WRFb-NoahMP and WRFb-CLM3.5 which use the KF scheme). It is however not possible to do more than just speculating without dedicated sensitivity experiments with WRF which would be beyond the scope of this study. Concerning the simulations based on CCLM, a recent study has examined the sensitivity to land cover changes in CLM4.5 (Meier et al., 2018) and can indeed provide insights on the interpretation of the differences seen between CCLM-CLM4.5 and the other CCLM configurations (see also response below).

Changes to manuscript: We added a discussion of the differences between WRFa-NoahMP and WRFb-NoahMP in section 3.3 focusing in particular on the role of the convection scheme for the precipitation response (these two configurations exhibit a diverging precipitation response in summer). We removed the old figure 12 so that we now discuss precipitation results only based on the difference maps in section 3.3. Indeed given that precipitation changes are small and arguably not necessarily significant, it does not seem justified to apply the cluster analysis on precipitation, which we now only apply on temperature.

Finally, the authors need to be more careful about the role of scale when discussing the impacts of changes in land cover on the coupled biosphere-atmosphere system. For example, the authors stated that simulated changes in diurnal cycle due to forest/grass cover are the opposite of what previous observations suggest (near line 230). While I agree that this deserves further analysis, we cannot ignore that the impacts of replacing the vegetation of an entire continent on the diurnal cycle of temperature ought to be completely different from the impact of patchy deforestation/afforestation. At least in the tropics, the extent of deforestation in tropical forests may completely change the impact of land cover change in precipitation (e.g. Spracklen et al. 2018, doi:10.1146/annurev-environ-102017-030136, and references therein), and I would imagine that scale would also matter in higher latitudes and in other variables.

Response: We totally agree that the issue of scale might be an important aspect here. Observational methods capture mainly local changes in surface energy balance and temperature due to land cover and are unlikely to reflect the type of larger scale atmospheric feedbacks that can be triggered in coupled models (especially given the drastic land cover change imposed). In other words, the apparent discrepancy between models and observations may in part arise from the fact that models and observations differ in the scale of processes considered (and we should therefore be more careful not to attribute this discrepancy only to a lack of model realism). We agree that it is important to emphasize this point more clearly in the paper.

Changes to manuscript: The discussion on observation-based evidence has been revised and now explicitly mentions that: "… this apparent contradiction may not be only attributable to model deficiencies and could be in part related to discrepancies in the scale of processes considered in models and observations. Indeed, observation-based estimates capture mainly local changes in surface energy balance and temperature due to land cover and are unlikely to reflect the type of large scale atmospheric feedbacks triggered in coupled climate models (especially given the large scale nature of the forest expansion considered in our experiments)." We also still emphasize the need for dedicated benchmarking efforts to tackle the issue of models to observations comparison.

Specific and minor comments
Abstract. It would be helpful if the authors quantified their statements. For example, when they say that the albedo decreased with forestation, they could provide the range so readers would be able to judge whether the changes are important or not. This also applies to the range of temperature responses.

Changes to manuscript: agreed, ranges of values for temperature were added to the abstract

Discussion. I found somewhat hard to judge most of the results because little information is provided about how these different models usually perform across Europe. For instance, it would be very helpful to know whether some of them always underestimate rainfall or overestimate evapotranspiration, for example. Ideally the authors could show some model assessment with known benchmarks, but I understand that the model cannot be validated for idealised simulations. One suggestion would be to include one or two paragraphs describing previous studies using these models.

Response: As noted by the reviewer, the type of extreme land cover experiments performed here are not suitable for classical evaluation purpose. However, most of the RCMs used in our study have been part of EURO-CORDEX and have been evaluated in this context (e.g. Kotlarski et al 2014; Davin et al. 2016). Although for a given RCM the version and configuration used in our study may differ from the published EURO-CORDEX counterpart, the systematic biases that have been previously identified are still relevant here (e.g. predominant cold and wet biases for most European regions with the exception of Southern Europe in summer where the opposite occurs). We agree that this context should be provided.

Changes to manuscript: We added a paragraph in section 2.1 describing previous evaluation results and the type of systematic biases found in these RCMs.

Line 36. Give concrete examples of atmospheric processes that dictate more directly the simulated response.

Changes to manuscript: We changed this sentence now explicitly referring to radiation/cloud feedbacks building upon the new correlation analysis introduced in this version.

Line 51. A better justification is needed for the opening sentence. One could still see some regional effects of land cover and land use change in global models, especially the extreme land cover scenarios used in this study.

Response: It is true that global models can also represent some regional LUC effects as we indeed summarize in the first paragraph. We are certainly not arguing that LUC should be included in RCMs rather than in GCMs, obviously it should be considered in both types of models. But the current situation is that RCMs intercomparison projects typically ignore LUC effects. We are therefore arguing that this should be remedied, one of the added values being (beside improving the consistency in forcings included in global and regional experiments) that new insights could be gained given the higher resolution at which RCMs operate (e.g. enabling to capture such local to regional effects in more details). While one could argue that this resolution issue is not critical in the extreme scenarios analyzed in the phase 1 of LUCAS, this nevertheless provides an essential motivation for the LUCAS project in general and beyond phase 1.

Changes to manuscript: We changed the opening sentence to avoid giving the impression that regional effects can only be seen in RCMs: “In this light, it is particularly important to represent LUC forcings not only in global climate models but also in regional climate simulations.”

Line 110-112. This is fine for the experiment, but the current approach does not completely prevent placing trees in areas naturally dominated by grasses or shrubs like some of the Mediterranean maquis.

Response: It is certainly true that the FOREST map does not represent a potential vegetation map. Our intention was indeed to generate a map of maximum forest coverage, which we thought was more meaningful to explore the full forestation potential. There are already many examples of places in Europe where trees are growing where they would not be the naturally occurring vegetation type simply because of human intervention (assisted afforestation, forest management, fire suppression, etc). Our forest map is therefore less conservative in terms of potential for tree expansion than a potential vegetation map, which is in line with the idea of considering both reforestation and afforestation potential (note that we still exclude forest expansion over drylands that would likely imply drastic irrigation measures).

Changes to manuscript: We added a paragraph in section 2.2 to clarify this point.

Section 3.1. Figures 3-6 are interesting, but I think you could move some of them to the SI, and bring some of the atmospheric figures that could help explaining these differences to the main text (e.g. net radiation or precipitation).

Changes to manuscript: We moved the shortwave radiation figures into the main text, but we chose to keep 3-6 as they are described in the text and the total number of figures (now 13) is not unreasonably high.

Line 162. One interesting feature is that all CLM runs (CCLM, WRF, RegCM) seem to show increases in ET during the spring, but not during the summer. Could this be an extreme response to drought stress, like the beta factor being too low that stomata are closed for most of the summer?

Response: This behavior has been analyzed in details in an offline study with CLM4.5 (Meier et al., 2018) which indeed concluded that there is a too strong water limitation effect (too low beta factor in forest compared to open land) in summer in CLM4.5, while ET is higher in spring under forested conditions. The fact that this occurs also in the context of offline simulations confirm that this is an intrinsic feature of the CLM land surface model. Meier et al., 2018 tested various modifications to alleviate this issue but these modifications were not included in the coupled RCMs which are based on the default version of CLM.

Changes to manuscript: We included a discussion on this particular behavior in CLM4.5 in the discussion section.

Lines 165-170. Add references to figures/tables.

Changes to manuscript: references to figures were added

Lines 169-170. The last sentence belong to discussion instead of results, and I think this deserves to be expanded a bit more: this is likely to be related to my previous comment. One possibility could be that trees may be transpiring too much during the spring then running out of water during the summer. However, this is not so clear over land in Fig. S11. The strongest negative tendencies seem to be over the Mediterranean Sea and Black Sea. Just to confirm, do the averages in Figures 7–10 exclude grid cells over water?

Changes to manuscript: This sentence has been moved to the discussion and expended. In particular the discussion is complemented by results from Meier et al., 2018 (see above). Averaged values indeed include only land points as mentioned in the first sentence of section 3.2.

Lines 185-189; lines 195-196; 212-213. If most of the variance in winter is not explained by albedo and evaporative fraction, then what is causing the variability? Could the variations be attributed to changes in weather patterns? The authors could and should include predictors that were not so surface-centric. The authors suggest that precipitation has no consensus amongst models (unsurprising, this is often more uncertain than other meteorological variables).

Response: It would be beyond the scope of this manuscript to analyze weather patterns given the focus on the mean seasonal response in temperature and surface energy balance (weather phenomena would require outputs at much higher temporal resolution). But we will expand the discussion on the role of atmospheric processes as already discussed above.

Changes to manuscript: Incoming radiation was added to the analysis of variance (see above). We also added a paragraph describing the role of precipitation changes in section 3.3.

Lines 228-232: I do not necessarily see an inconsistency between model and independent observations. Europe is not a grassland continent nor a forest continent, and when an entire continent changes land cover, then the response will be very different from patches of forest next to patches of grassland that are side by side.

Response: We agree that the scale effect can play an important role here.

Changes to manuscript: This paragraph has been reformulated (see response above).

Line 242-243. I agree with this sentence, but the authors did not provide any insight on this. The authors could at least use the simulations in which differences are contained to indicate some of the origin of uncertainties. This would make the discussion much more interesting and informative, and go beyond the "models showed little or no agreement" storyline that we often see in model intercomparison papers.

Response: This sentence is about differences between surface versus 2-meter temperature. We agree that we did not give a lot of insights on this point (other than showing maps of surface temperature changes in the SI), but a separate study within LUCAS is exploring specifically the issue of surface versus 2-meter temperature (Breil et al., submitted). We therefore decided to focus only on 2-meter temperature results here and consistently use only 2-meter temperature across the entire manuscript.

Changes to manuscript: This sentence was removed as well as the SI figure for surface temperature.

Table 1.
- *I found this table a bit hard to read, I wonder if it would make it easier to separate the atmospheric and land surface settings.*
- *Was there any reason why the spin-up period was different for the three WRF simulations?*
- *In the greenhouse gas row, What is the difference between historical and constant? I assume historical means time varying, but this should be clarified, and a citation should be provided. For the simulations with constant values, provide these values, at least for CO2.*

Response: The spin-up in WRFb-Noah and WRFb-CLM3.5 is shorter only due to computational constraints.

Changes to manuscript: We now included a separation within the table between "land settings" and "atmospheric settings". We condensed the table using acronyms for the definition of vegetation types which overall improved the readability. We provide the constant CO2 values and the reference for the transient GHG.

Figures 1-6. What is MMM? I assume that it is the average response. Explain this in the figure captions.

Changes to manuscript: We added in section 2.1 that MMM means Multi-Model Mean.

Figure 9. Consider adding a similar panel for the Mediterranean.

Changes to manuscript: Thank you for this suggestion. We added a second panel for the same region (Scandinavia) but illustrating the relation between changes in albedo and temperature since this is one of the important driving factor described in the text.

Referee #2

The paper addresses relevant scientific questions. There was a strong effort of several groups in order to provide modeling results and evaluate the modeling physics of several systems. The intercomparison of the surface and atmospheric modeling systems and the two experiments (i.e. total FOREST x GRASS) provides an interesting tool for modeling improvement, mainly on the understanding the LSM impacts and feed-backs. The modeling results provide a new original contribution. The methodology is appropriated for the goals of the project. It provides variable Land Surface Systems and various atmospheric options. The paper structure has a good flow and fluency. See some questions & suggestions below.

The results show that there were several differences among the modeling systems used on the inter-comparison. I think on the methodology more information should be provided by the authors, mainly on the soil types and vegetation parameters such as the maximum/minimum stomatal resistance, *vegetation height, and roots depth. Those parameters could allow improvements on the major conclusions. Furthermore, it could help the reproduction of the numerical experiments.*

Response: It is certainly conceivable that vegetation parameters could explain some of the differences between models. However, we don't think that listing these parameters will significantly shed light on the potential sources of model differences (mainly because it will not be possible to disentangle the effect of these parameters from the effect of other parameters/parameterization). That said, one particular feature of our RCM ensemble is that some RCMs are used in different configurations with a limited set of differences (e.g. WRF family) which can be an advantage when trying to attribute differences in model response to specific processes. We will therefore strengthen the discussion around specific parameterization differences in these models in order to make a clearer link between process representation and differences in simulated response (see also response to reviewer 1). Concerning specifically the role of vegetation parameters, a recent study using CLM4.5, which is also use here in two RCMs, investigated the role of vegetation/root parameters and water uptake parameterization on the simulated effect grass to forest conversion (Meier et al., 2018). Since these results can help understand the behavior of the RCMs using CLM we will provide a discussion with a link to this study.

Changes to manuscript: In various places we added more discussion on the link between process representation and differences in simulated response. We added for instance a paragraph on the role of the convection scheme in WRF (section 3.3) and a paragraph on the role of specific land parameters (root distribution and photosynthetic parameters) in the discussion section (see also response to reviewer 1).

The results discussions on the maps of temperature, don't provide analysis of map MMM (e.g. Figs 1 to 6). What are those maps? Mean of all modeling systems?

Changes to manuscript: We explicitly added the meaning of MMM (Multi-Model Mean, i.e. mean over all RCMs) in section 2.1.

Precipitation maps should be better analyzed in order to improve the conclusions on the temperature fields. Surface changes are likely to change the precipitation fields and as a feedback, the precipitation distribution is likely to have an impact the balance of radiation (downward and upward) and surface conditions, such as soil moisture and temperature.   Furthermore, maps of precipitation could help on the interpretation of the discrepancies among models because this variable controls the vegetation transpiration, downward and upward short wave radiation, among others. Forest versus grass simulations for the Amazon, for instance, shows a strong change on the precipitation distribution caused by the transpiration (e.g. Ramos-da-Silva et al., J. Climate2008).

Response: Maps of precipitation changes are already provided (fig S5), but are indeed not central in our paper due to the focus on temperature and energy balance changes. We nevertheless added a paragraph to describe precipitation change and potential feedbacks.

Changes to manuscript: We added a paragraph on precipitation and precipitation feedbacks in section 3.3 mentioning that precipitation changes are small but may play a role in the context of specific models such as WRF: "We note however that precipitation changes are small in all RCMs with no clear consensus among models (Fig. S5). One possible exception is the summer precipitation decrease in WRFa-NoahMP which could be related to the use of the Grell-Freitas convection scheme (Table 1), while precipitation is less affected in WRFb-NoahMP and WRFb-CLM3.5 which use the Kain-Fritsch scheme. The stronger summer temperature increase in WRFa-NoahMP compared to WRFb-NoahMP and WRFb-CLM3.5 may therefore be linked to this precipitation feedback."

The authors should provide some insights on: how the forestation affects the major synoptic systems that move across Europe? Are these atmospheric systems enhanced or weakened?

Response: We agree that this aspect would warrant further analysis but we believe this is well beyond the scope of this paper which focuses on the mean seasonal climate response to forestation (we use monthly mean outputs in this study). Addressing changes in weather systems would require analysis at much higher temporal resolution which is the scope of an additional study currently being prepared by the LUCAS team (Strandberg et al., in prep.)

Changes to manuscript: Although we did not address this point directly, we added incoming shortwave radiation in the correlation analysis thus proving additional insights on atmospheric processes (see response to reviewer #1).

To improve the results analysis and discussion, known LSM model bias from previous studies could help on the results interpretation (e.g. Chen etal., JGR 2014).

Changes to manuscript: Agreed, we added a paragraph in section 2.1 describing previous evaluation results and the typical systematic biases present in RCMs which provides an important context for this study (see also response to reviewer 1).

Some figures should be improved. Better legends could help the readers to quickly understand the presented images. For instance, what is MMM on the maps? Furthermore, in some figures, the fonts needs to be higher to permit a better reading (e.g. Figures 7, 8, 9 and 10). Figure 7 should have a higher threshold for net radiation. It is not clear the maximum on some cases.

Changes to manuscript: We clarified the meaning of MMM (Multi-Model Mean) and we changed the range of figures.

Further minor text corrections: Table 01 – Lateral boundary in the last column should be exponential (not expotential)

Changes to manuscript: corrected

Discussion – line 235-236 should be evapotranspiration (not evaporation)

Changes to manuscript: corrected

Additional notes from the authors:

1) A minor correction was made to the REMO-iMOVE simulations. The new version of these simulations were integrated to this revised version resulting only in minor differences without any changes to the conclusions.
2) In the submitted version, the wrong figure was used for panel b in figure 13 (due to a mistake in the season considered). This is corrected in this revised version.

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Biogeophysical impacts of forestation in Europe: First results from the LUCAS Regional Climate Model intercomparison

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Abstract. The Land Use and Climate Across Scales Flagship Pilot Study (LUCAS FPS) is a coordinated community effort to improve the integration of Land Use Change (LUC) in Regional Climate Models (RCMs) and to quantify the biogeophysical effects of LUC on local to regional climate in Europe. In the first phase of LUCAS, nine RCMs are used to explore the biogeophysical impacts of re-/afforestation over Europe. Namely, two idealized experiments representing respectively a non-forested and a maximally forested Europe are compared in order to quantify spatial and temporal variations in the regional climate sensitivity to forestation. We find some robust features in the simulated response to forestation. In particular, all models indicate a year-round decrease in surface albedo, which is most pronounced in winter and spring at high latitudes. This results in a winter warming effect, with values ranging from +0.2 to +1 K on average over Scandinavia depending on models. However, there are also a number of strongly diverging responses. For instance, there is no agreement on the sign of temperature changes in summer with some RCMs predicting a widespread cooling from forestation (well below -2 K in most regions), a widespread warming (around +2 K or above in most regions), or a mixed response. A large part of the inter-model spread is attributed to the representation of land processes. In particular, differences in the partitioning of sensible and latent heat are identified as a key source of uncertainty in summer. Atmospheric processes, such as changes in incoming radiation

due to cloud cover feedbacks, also influence the simulated response in most seasons. In conclusion, the multi-model approach we use here has the potential to deliver more robust and reliable information to stakeholders involved in land use planning, as compared to results based on single models. However, given the contradictory responses identified, our results also show that there are still fundamental uncertainties that need to be tackled to better anticipate the possible intended or unintended consequences of LUC on regional climates.

1 Introduction

Land Use Change (LUC) affects climate through biogeophysical processes influencing surface albedo, evapotranspiration and surface roughness (Bonan 2008; Davin and de Noblet-Ducoudre 2010). The quantification of these effects is still subject to particularly large uncertainties, but there is growing evidence that LUC is an important driver of climate change at local to regional scales. For instance, the Land-Use and Climate, IDentification of robust impacts (LUCID) model intercomparison indicated that while LUC likely had a modest biogeophysical impact on global temperature since the pre-industrial era, it may have affected temperature in similar proportion as greenhouse gas forcing in some regions (de Noblet-Ducoudre et al. 2012). Results from the Coupled Model Intercomparison Project Phase 5 (CMIP5) confirmed the importance of LUC for regional climate trends and for temperature extremes (Lejeune et al. 2017, 2018; Kumar et al. 2013).

In this light, it is particularly important to represent LUC forcings not only in global climate models but also in regional climate simulations. Yet, LUC forcings were not included in previous RCM intercomparisons (Christensen and Christensen 2007; Jacob et al. 2014; Mearns et al. 2012; Solman et al. 2013), which are the basis for numerous regional climate change assessments providing information for impact studies and the design of adaptation plans (Gutowski Jr. et al. 2016). RCMs have been applied individually to explore different aspects of land use impacts on regional climates (Gálos et al. 2013; Davin et al. 2014; Lejeune et al. 2015; Wulfmeyer et al. 2014; Tölle et al. 2018), but the robustness of such results is difficult to assess due to their reliance on single RCMs and to the lack of a common protocol. There is therefore a need for a coordinated effort to better integrate LUC effects in RCM projections. The Land Use and Climate Across Scales (LUCAS) initiative (https://www.hzg.de/ms/cordex-fps-lucas/) has been designed with this goal in mind. LUCAS is endorsed as a Flagship Pilot Study (FPS) by the World Climate Research Program-Coordinated Regional Climate Downscaling Experiment (WCRP-CORDEX) and was initiated by the European branch of CORDEX (EURO-CORDEX) (Rechid et al. 2017). The objectives of the LUCAS FPS are to promote the inclusion of the missing LUC forcing in RCM multi-model experiments and to identify the associated impacts with a focus on regional to local scales and considering time scales from extreme events to seasonal and multi-decadal trends and variability. LUCAS is designed in successive phases that will go from idealized to realistic high-resolution scenarios and intend to cover both land cover changes and land management impacts.

In the first phase of LUCAS, which is the focus of this study, idealized experiments over Europe are performed in order to benchmark the RCMs sensitivity to extreme LUC. Two experiments (FOREST and GRASS) are performed using a set of nine RCMs. The FOREST experiment represents a maximally forested Europe, while in the GRASS experiment trees are replaced by grassland. Comparing FOREST to GRASS therefore indicates the theoretical potential of a maximum forestation (encompassing both reforestation and afforestation) scenario over Europe. Given that forestation is one of the most prominent land-based mitigation strategies put forward in scenarios compatible with the Paris Agreement goals (Grassi et al. 2017; Harper et al. 2018; Griscom et al. 2017), it is therefore essential to understand its full consequences beyond CO_2 mitigation. These experiments are not meant to represent realistic scenarios but they enable a systematic assessment and mapping of the biogeophysical impact of forestation across regions and seasons. Experiments of this type have already been performed using single regional or global climate models (Claussen et al. 2001; Davin and de Noblet-Ducoudre 2010; Cherubini et al. 2018; Strandberg et al. 2018), but here they are performed for the first time using a multi-model ensemble approach, thus providing an unprecedented opportunity to assess uncertainties in the climate response to vegetation perturbations. In the following, we focus on the analysis of the surface energy balance and temperature response at the seasonal time scale, while future studies within LUCAS will explore further aspects (e.g. sub-daily time scale and extreme events, land-atmosphere coupling, etc). We aim to quantify the potential effect of forestation over Europe, identify robust model responses and investigate the possible sources of uncertainty in the simulated impacts.

2 Methods

2.1 RCM ensemble

Two experiments (GRASS and FOREST) were performed with an ensemble of nine RCMs whose names and characteristics are presented in Table 1. All experiments were performed at 0.44 degree (~50km) horizontal resolution on the EURO-CORDEX domain (Jacob et al. 2014) with lateral boundary conditions and sea surface temperatures prescribed based on 6-hourly ERA-Interim reanalysis (Dee et al. 2011). The simulations are analysed over the period 1986-2015 and the earlier years (1979-1985, or a subset of these years depending on models, see Table 1) were used as spin-up period. The model outputs were aggregated to monthly values for use in this study. When showing results averaged across all nine RCMs, we refer to it as the Multi-Model Mean (MMM).

A notable characteristic of the multi-model ensemble is that some RCMs share the same atmospheric scheme (i.e. same version and configuration) but are coupled to different Land Surface Models (LSMs), or share the same LSM in combination with different atmospheric schemes (see Table 1). This allows to evaluate the respective influence of atmospheric versus land processes representation. For instance, the same version of COSMO-CLM (CCLM) is used in combination with three different LSMs (TERRA_ML, VEG3D and CLM4.5). Comparing results from these three CCLM-based configurations enables to isolate the role of land processes representation in this particular model. Conversely, CLM4.5 is used in combination with two different RCMs (CCLM and RegCM) which allows to diagnose the influence of atmospheric processes on the results. Different configurations of WRF are also used: WRFa-NoahMP and WRFb-NoahMP differ only in their atmospheric setup, while WRFb-NoahMP and WRFb-CLM3.5 share the same atmospheric setup but with different LSMs.

While the simulations we present are not suitable for model evaluation because of the idealized land cover characteristics, it is worthwhile to note that the RCMs included here have been part of previous evaluation studies over Europe (e.g., Kotlarski et al. 2014; Davin et al. 2016). Although for a given RCM the model version and configuration may differ from previously evaluated configurations, the systematic biases highlighted in these previous studies are likely still relevant here. In particular, a majority of RCMs suffer from predominantly cold and wet biases in most European regions, while the opposite is true in summer in Mediterranean regions (Kotlarski et al. 2014). The too dry conditions over Southern Europe have been related in particular to land surface processes representation including evapotranspiration (Davin et al. 2016).

2.2 FOREST and GRASS vegetation maps

Two vegetation maps have been created for use in the Phase 1 LUCAS experiments (Fig. S1). The vegetation map used in experiment FOREST is meant to represent a theoretical maximum of tree coverage, while in the vegetation map used in experiment GRASS, trees are entirely replaced by grassland.

The starting point for both maps is a MODIS-based present-day land cover map at 0.5 degree resolution (Lawrence and Chase 2007) providing the global distribution of 17 Plant Functional Types (PFTs). Crops and shrubs which are present in the original map are not considered in the FOREST and GRASS experiments and are set to zero. To create the FOREST map, the fractional coverage of trees is expanded until trees occupy 100% of the non-bare soil area. The proportion of various tree types (i.e. broadleaf/needleleaf and deciduous/evergreen) is conserved as in the original map as well as the fractional coverage of bare soil which prevents expanding vegetation on land areas where it could not realistically grow (e.g. in deserts). If no trees are present in a given grid cell with less than 100% bare soil, the zonal mean forest composition is taken as a representative value. This results in a map with only tree PFTs (PFT names) and bare soil, all other vegetation types being shrunk to zero. It is important to note that this FOREST map does not represent a potential vegetation map, which would imply a more conservative assumption in terms of forest expansion potential. Indeed, trees can grow even in regions where they would not naturally occur because of various human interventions (assisted afforestation, forest management, fire suppression, etc). This FOREST map is therefore in line with the idea of considering both reforestation and afforestation potential, while still excluding forest expansion over dryland regions where irrigation measures would likely be necessary.

The GRASS map is then derived from the FOREST map by converting all tree PFTs into grassland PFTs, the C3 to C4 ratio being conserved as in the original MODIS-based map as well as the bare soil fraction.

Since the various RCMs use different land use classification schemes (see Table 1), the PFT-based FOREST and GRASS maps were converted into model-specific land use classes for implementation into the respective RCMs. The specific conversion rules used in each RCM are summarized in Table 1 (note that for three out of the nine RCMs no conversion was required). Urban areas, inland water and glacier, if included in a given RCM, were conserved as in the standard dataset of the respective RCM.

Table 1: Names and characteristics of the RCMs used. NET-Temperate: Needleleaf evergreen tree – temperate; NET-Boreal: Needleleaf evergreen tree - boreal; NDT-Boreal: Needleleaf deciduous tree - boreal; BET-Tropical: Broadleaf evergreen tree - tropical; BET-Temperate: Broadleaf evergreen tree - temperate; BDT-Tropical: Broadleaf deciduous tree - tropical; BDT-Temperate: Broadleaf deciduous tree - temperate; BDT-Boreal: Broadleaf deciduous tree - boreal; BES-Temperate: Broadleaf evergreen shrub - temperate; BDS-Temperate: Broadleaf deciduous shrub - temperate; BDS-Boreal: Broadleaf deciduous shrub - boreal.

Model name	**CCLM-TERRA**	**CCLM-VEG3D**	**CCLM-CLM4.5**	**RCA**	**RegCM-CLM4.5**	**REMO-iMOVE**	**WRFa-NoahMP**	**WRFb-NoahMP**	**WRFb-CLM3.5**
Institute ID	JLU/BTU/CMCC	KIT	ETH	SMHI	ICTP	GERICS	IDL	UHOH	AUTH
RCM	COSMO_5.0_clm9	COSMO_5.0_clm9	COSMO_5.0_clm9	RCA4	RegCM4.6.1 (Giorgi et al. 2012)	REMO2009	WRF381	WRF381	WRF381
Land settings									
Land surface scheme	TERRA-ML (Schrodin and Heise 2002)	VEG3D (Breil et al. 2018)	CLM4.5 (Oleson et al. 2013)	(Samuelsson et al. 2006)	CLM4.5 (Oleson et al. 2013)	iMOVE (Wilhelm et al. 2014)	NoahMP	NoahMP	CLM3.5 (Oleson et al. 2008)
Land cover classes (classes effectively used in FOREST and GRASS in bold)	**1: BET** **2: BDT closed** **3: BDT open** **4: NET** **5: NDT** 6: mixed leaf trees 7: fresh water flooded trees 8: saline water flooded trees 9: mosaic tree/natural veget. 10: burnt tree cover 11: everg. shupbs closed/open 12: desc. shrubs closed/open 13: herbac. veget. closed/open **14: grass** 15: flooded shrups or herbac. 16: cultivated and managed	**1: bare soil** 2: water 3: urban **4: deciduous forest** **5: coniferous forest** 6: mixed forest 7: cropland 8: special crops **9: grassland** 10: shrubland	**1: Bare Soil** **2: NET-Temperate** **3: NET-Boreal** **4: NDT-Boreal** 5: BET-Tropical **6: BET-Temperate** 7: BDTree-Tropical **8: BDT-Temperate** **9: BDT-Boreal** 10: BDS-Temperate 11: BES-Temperate 12: BDS-Boreal **13: C3 artic grass** **14: C3 grass** **15: C4 grass** 16: Crop 1 17: Crop 2	**1: bare soil** **2: open land** **3: needle leaf forest** **4: broad leaf forest**	**1: Bare Soil** **2: NET-Temperate** **3: NET-Boreal** **4: NDT-Boreal** 5: BET-Tropical **6: BET-Temperate** 7: BDTree-Tropical **8: BDT-Temperate** **9: BDT-Boreal** 10: BDS-Temperate 11: BES-Temperate 12: BDS-Boreal **13: C3 artic grass** **14: C3 grass** **15: C4 grass** 16: Crop 1 17: Crop 2	**1: tr. br. everg.** **2: tr. br. desc.** **3: temp. br. everg.** **4: temp. br. desc.** **5: everg. conif.** **6: desc. conif.** 7: everg. shrubs 8: desc. shrubs **9: C3 grasses** **10: C4 grasses** 11: tundra 12: swamps 13: C3 crops 14: C4 crops 15: urban **16: bare**	**1: NET** **2: NDT** 3: BET **4: BDT** 5: mixed forests 6: closed shrubland 7: open shrubland 8: wooded savannah 9: savannah **10: grassland** 11: wetlands 12: cropland 13: urban and built-up 14: cropland/natural vegetation mosaic **15: snow and ice** **16: barren or sparsely vegetated** **17: water** 18: wooded tundra 19: mixed tundra 20: barren	**1: NET** **2: NDT** 3: BET **4: BDT** 5: mixed forests 6: closed shrubland 7: open shrubland 8: wooded savannah 9: savannah **10: grassland** 11: wetlands 12: cropland 13: urban and built-up 14: cropland/natural vegetation mosaic **15: snow and ice** **16: barren or sparsely vegetated** **17: water** 18: wooded tundra 19: mixed tundra 20: barren	**1: NET** **2: NDT** 3: BET **4: BDT** 5: mixed forests 6: closed shrubland 7: open shrubland 8: wooded savannah 9: savannah **10: grassland** 11: wetlands 12: cropland 13: urban and built-up 14: cropland/natural vegetation mosaic **15: snow and ice** **16: barren or sparsely vegetated** **17: water** 18: wooded tundra 19: mixed tundra

	17: mosaic crop/tree/net veget. 18: mosaic crop/shrub/grass **19: bare areas** 20: water 21: snow and ice 22. artificial surface 23: undefined						tundra 21: lakes	tundra 21: lakes	20: barren tundra 21: lakes
Conversion method to implement the PFT-based input vegetation maps (FOREST and GRASS)	bare soil=19 NET-Temperate=4 NET-Boreal=4 NDT-Boreal=5 BET-Temperate=1 BDT-Temperate=2 BDT-Boreal=3 C3 arctic grass= 14 C3 grass= 14 C4 grass= 14	bare soil=1 NET-Temperate=5 NET-Boreal=5 NDT-Boreal=5 BET-Temperate=4 BDT-Temperate=4 BDT-Boreal=4 C3 arctic grass =9 C3 grass =9 C4 grass =9	No conversion needed	Bare soil = 1 NET-Temperate = 3 NET-Boreal = 3 NDT-Boreal = 3 BET-Temperate = 4 BDT-Temperate = 4 BDT-Boreal = 4 C3 arctic grass = 2 C3 grass = 2 C4 grass = 2	No conversion needed	bare soil=16 NET-Temperate=5 NET-Boreal=5 NDT-Boreal=6 BET-Temperate=3 BDT-Temperate=4 BDT-Boreal=4 C3 arctic grass=9 C3 grass=9 C4 grass=10	Bare soil = 16 NET-Temperate = 1 NET-Boreal = 1 NDT-Boreal = 2 BET-Temperate = 3 BDT-Temperate = 4 BDT-Boreal = 4 C3 arctic grass = 10 C3 grass = 10 C4 grass = 10	Bare soil = 16 NET-Temperate = 1 NET-Boreal = 1 NDT-Boreal = 2 BET-Temperate = 3 BDT-Temperate = 4 BDT-Boreal = 4 C3 arctic grass = 10 C3 grass = 10 C4 grass = 10	Bare soil = 16 NET-Temperate = 1 NET-Boreal = 1 NDT-Boreal = 2 BET-Temperate = 3 BDT-Temperate = 4 BDT-Boreal = 4 C3 arctic grass = 10 C3 grass = 10 C4 grass = 10
Representation of sub-grid scale vegetation heterogeneity	Single class	Single class	Tile approach	Tile approach	Tile approach	Tile approach	Single class	Single class	Tile approach
Leaf Area Index	Prescribed seasonal cycle (sinus function depending on altitude and latitude with vegetation-dependent minimum and maximum values)	Prescribed seasonal cycle (sinus function depending on altitude and latitude with vegetation-dependent minimum and maximum values)	Prescribed seasonal cycle based on MODIS (Lawrence and Chase 2007)	Calculated monthly based on vegetation type, soil temperature and soil moisture	Prescribed seasonal cycle based on MODIS (Lawrence and Chase 2007)	Calculated daily based on atmospheric forcing and soil moisture state	Prescribed seasonal cycle based on lookup tables	Prescribed seasonal cycle based on lookup tables	Prescribed seasonal cycle based on MODIS (Lawrence and Chase 2007)
Total soil depth and number of hydrologically /thermally	9 thermally active layers down to 7.5	9 layers down to 7.5 m	15 layers for thermal calculations down to 42 m; first 10	5 layers down to 2.89 m	15 layers for thermal calculations down to 42 m; first 10	5 thermally active layers down to 10 m; 1 water bucket	4 layers down to 1 m	4 layers down to 1 m	10 layers down to 3.43 m

active soil layers	m; first 8 hydrologically active down to 3.9 m		hydrologically active down to 3.43 m		hydrologically active down to 3.43 m				
Atmospheric settings									
Initialisation and spin up	Initialization with ERA-Interim, 1979-1985 as spin-up	Initialization with ERA-Interim, 1979-1985 as spin-up	Initialization with ERA-Interim, 1979-1985 as spin-up	Initialization with ERA-Interim, 1979-1985 as spin-up	Initialization with ERA-Interim except soil moisture which is based on a climatological average (Giorgi et al. 1989); 1985 as spin-up	Initialization with ERA-Interim, 1979-1985 as spin-up	Initialization with ERA-Interim, 1979-1985 as spin-up	Initialization with ERA-Interim, 1983-1985 as spin-up	Initialization with ERA-Interim, 1984-1985 as spin-up
Lateral boundary formulation	(Davies 1976)	(Davies 1976)	(Davies 1976)	(Davies 1976) with a cosine-based relaxation function	(Giorgi et al. 1993)	(Davies 1976)	exponential relaxation	exponential relaxation	exponential relaxation
Buffer (No. of grid cells)	13	13	13	8	12	8	15	10	10
No. of vertical levels	40	40	40	24	23	27	50	40	40
Turbulence and planetary boundary layer scheme	Level 2.5 closure for turbulent kinetic energy as prognostic variable (Mellor and Yamada 1982)	Level 2.5 closure for turbulent kinetic energy as prognostic variable (Mellor and Yamada 1982)	Level 2.5 closure for turbulent kinetic energy as prognostic variable (Mellor and Yamada 1982)	(Vogelezang and Holtslag 1996)	The University of Washington turbulence closure model (Grenier et al. 2001; Bretherton et al. 2004)	Vertical diffusion after (Louis 1979) for the Prandtl layer, extended level-2 scheme after (Mellor and Yamada 1974) in the Ekman layer and the free atmosphere including modifications in the presence of clouds	MYNN Level 2.5 PBL (Nakanishi and Niino 2006; NAKANISHI and NIINO 2009)	MYNN Level 2.5 PBL (Nakanishi and Niino 2006; NAKANISHI and NIINO 2009)	MYNN Level 2.5 PBL (Nakanishi and Niino 2006; NAKANISHI and NIINO 2009)
Radiation scheme	(Ritter et al. 1992)	(Ritter et al. 1992)	(Ritter et al. 1992)	(Savijärvi and Savijärvi 1990), Wyser et al (1999)	Radiative transfer model from the NCAR Community Climate Model 3 (CCM 3) (Kiehl et al., 1996)	(Morcrette et al. 1986) with modifications for additional greenhouse gases, ozone and various aerosols.	Rapid Radiative Transfer Model (RRTMG) scheme (Iacono et al. 2008)	Rapid Radiative Transfer Model (RRTMG) scheme (Iacono et al. 2008)	Rapid Radiative Transfer Model (RRTMG) scheme (Iacono et al. 2008)
Convection scheme	(Tiedtke 1989)	(Tiedtke 1989)	(Tiedtke 1989)	(Bechtold et al. 2001)	(Tiedtke 1996) for	(Tiedtke 1989) with modification	(Grell and Freitas 2014) for cumulus	(Kain 2004); no shallow convection	(Kain 2004); no

					cumulus convection	s after Nordeng (1994)	convection and Global/Regional Integrated Modeling System (GRIMS) Scheme (Hong et al. 2013) for shallow convection		shallow convection
Microphysics scheme	One-moment cloud microphysics scheme (Seifert and Beheng 2001)	One-moment cloud microphysics scheme (Seifert and Beheng 2001)	One-moment cloud microphysics scheme (Seifert and Beheng 2001)	Values from tables	Subgrid Explicit Moisture scheme (SUBEX) (Pal et al. 2000)	(Sundqvist 1978)(Roeckner et al., 1996)	Two-moment, 6-class scheme (Lim and Hong 2010)	(Thompson et al. 2004)	(Thompson et al. 2004)
Greenhouse gases	Historical (Meinshausen et al. 2011)	Historical (Meinshausen et al. 2011)	Historical (Meinshausen et al. 2011)	Historical (Meinshausen et al. 2011)	Historical (Meinshausen et al. 2011)	Historical (Meinshausen et al. 2011)	Historical (Meinshausen et al. 2011)	Constant (CO_2 = 379 ppm)	Constant (CO_2 = 379 ppm)
Aerosols	Constant (Tanré, 1984)	(Tegen et al. 1997) climatology	Constant (Tanré, 1984)	Constant	Not accounted for	Constant (Teichmann et al. 2013)	(Tegen et al. 1997) climatology	(Tegen et al. 1997) climatology	(Tegen et al. 1997) climatology

3 Results

3.1 Temperature response

The effect of forestation (FOREST minus GRASS) on seasonal mean winter 2-meter temperature is shown in Figure 1. All RCMs simulate a warming pattern which is strongest in the northeast of Europe. This warming effect weakens toward the southwest of the domain even changing sign for instance in the Iberian Peninsula (except for REMO-iMOVE). In summer (Fig. 2), there is a very large spread of model responses with some RCMs predicting a widespread cooling from forestation (CCLM-TERRA and RCA), a widespread warming (RegCM-CLM4.5, REMO-iMOVE and the WRF models) or a mixed response (CCLM-VEG3D and CCLM-CLM4.5). This overall highlights the strong seasonal contrasts in the temperature effect of forestation and the larger uncertainties associated with the summer response.

Looking separately at the response for daytime and nighttime 2-meter temperatures also indicates important diurnal contrasts. The winter warming effect is stronger and more widespread for daily maximum temperature (Fig. 3), while daily minimum temperature shows a more contrasted cooling-warming dipole across the domain (Fig. 5). In summer, diurnal contrasts are even more pronounced with a majority of models showing an opposite sign of change for daily maximum and minimum temperatures over most of Europe (Fig. 4 and 6), namely a daytime warming effect and a nighttime cooling effect. Exceptions are RCA and CCLM-TERRA which indicate a cooling for both daily maximum and minimum temperatures and REMO-iMOVE exhibiting a warming for both daytime and nighttime.

In terms of magnitude, the temperature signal is substantial. In all RCMs, there is at least one season with absolute temperature changes above 2 degrees in some regions, for instance in winter and spring over Northern Europe (Fig. S2). The magnitude of changes is even more pronounced for daily maximum temperature.

3.2 Surface energy balance

Changes in surface energy fluxes over land are summarized for eight European regions (the Alps, the British Isles, Eastern Europe, France, the Iberian Peninsula, the Mediterranean, Mid-Europe and Scandinavia) as defined in the PRUDENCE project (Christensen et al. 2007). Here we discuss results for two selected regions representative of Northern Europe (Scandinavia; Fig. 9) and Southern Europe (the Mediterranean; Fig. 10), while results for the full set of regions are provided in the Supplementary Information (Fig. S11 to S18). One of the most robust features across models and seasons is an increase in surface net shortwave radiation. This increase is a direct consequence of the impact of forestation on surface albedo. Indeed all RCMs consistently simulate a year-round decrease in surface albedo due to the lower albedo of forest compared to grassland (Fig S7). This decrease is strongest in winter and at high latitudes owing to the snow masking effect of forest. However, the strongest increase in net shortwave radiation occurs in spring and summer in both regions because incoming radiation is higher in these seasons, thus implying a larger surface radiation gain despite the smaller absolute change in albedo. Notable outliers are REMO-iMOVE, exhibiting a smaller albedo decrease across all seasons and thus a less pronounced increase in net shortwave radiation, and CCLM-TERRA and RCA, which despite the albedo increase simulate a net shortwave radiation decrease in summer (only over Scandinavia in the case of RCA). In the latter two models, an increase in evapotranspiration triggers an increase in cloud cover and a subsequent decrease in incoming shortwave radiation (not shown) offsetting the change in surface albedo. The spatial pattern of surface net shortwave radiation change is relatively consistent across RCMs in winter with maximum net shortwave radiation increases well above 10 W/m^2 in high-elevation regions and the northeast of Europe (Fig. 7). In summer, the magnitude of net shortwave radiation changes is overall larger as well as the inter-model spread (Fig. 8). CCLM-TERRA is the only RCM to simulate a widespread decrease in net shortwave radiation, while RCA and CCLM-VEG3 also simulate net shortwave radiation decreases in some areas in particular in Northern Europe. All other RCMs simulate a widespread increase in net shortwave radiation over land, with WRFa-NoahMP and WRFb-NoahMP exhibiting the strongest increase with values well above 20 W/m^2 in most regions.

To a large extent, sensible heat flux follows shortwave radiation changes (i.e. a majority of models suggest an increase in sensible heat). This is also largely the case for ground heat flux (calculated here indirectly as the residual of the surface energy balance) which increases in autumn, winter and spring in most models due to the overall increase in absorbed radiation. Changes in the latent heat flux exhibit a higher degree of disagreement across models and seasons. For instance in spring, latent heat flux increases together with sensible heat over Scandinavia (Fig. 9) while it decreases in most models over the

Mediterranean (Fig. 10). In summer, the agreement is low over Scandinavia and there is a tendency for decreasing latent heat in the Mediterranean. At the European scale, there is a clear tendency of increasing latent heat flux in spring particularly over Northern Europe, whereas in summer most RCMs (with the exception of CCLM-TERRA) indicate both increasing and decreasing latent heat depending on regions (Fig. S10).

3.3 Origin of the inter-model spread

Changes in albedo and in the partitioning of turbulent heat fluxes are essential in determining the temperature effect of forestation. The dominant influence of albedo decrease is evident in winter and spring over Northern Europe as illustrated for instance by the quasi-linear inter-model relationship between the magnitude of changes in albedo and in 2-meter temperature over Scandinavia in spring (Fig. 11a). The role of turbulent heat fluxes partitioning can be illustrated by examining changes in evaporative fraction (EF), calculated as the ratio between latent heat and the sum of latent and sensible heat. The advantage of using EF instead of latent heat flux is that the former provides a metric relatively independent of albedo change (since albedo change does influence the magnitude of turbulent heat fluxes through changes in available energy). Taking the example of Scandinavia in summer (Fig. 11b), it appears that there is a relatively linear relationship between changes in temperature and in EF. In other words, models showing a decrease in EF following forestation tend to simulate a warming and models showing an increase in EF simulate a cooling.

In order to assess more systematically the role of individual drivers across regions and seasons, we perform a regression analysis using changes in albedo, EF and incoming surface shortwave radiation as explanatory variables and 2-meter temperature as the variable to be explained. The rationale for using albedo, EF and incoming surface shortwave radiation as explaining factors is that the first two capture the intrinsic LUC-induced changes in land surface characteristics representing respectively the radiative and non-radiative impacts of LUC, whereas incoming surface shortwave radiation captures some of the potential subsequent atmospheric feedbacks (e.g., through cloud cover changes). Here we discuss the results of the regression analysis for Scandinavia and the Mediterranean (Fig. 12), while results for the full set of regions are provided in the Supplementary Information (Fig. S19 and S20). Combining albedo, EF and incoming surface shortwave radiation into a multiple linear regression effectively explains a large fraction of the inter-model variance of the simulated temperature response (around 80% of variance explained for both regions and all seasons except winter where the explained variance is much lower). Albedo change alone explains the largest part of the inter-model variance in spring over Scandinavia and in winter over the Mediterranean, indicating a dominance of radiative processes during these seasons. EF change alone explains the largest part of the inter-model variance in summer over Scandinavia and in spring, summer and autumn over the Mediterranean. Finally, incoming surface shortwave radiation explains a substantial part of the inter-model variance across most seasons although it is not a dominating factor. It is important to note the two main caveats of this simplified approach: 1) The explanatory variables are likely not fully independent due to the tightly coupled processes in the models 2) Other factors not included as explanatory variables may contribute to the temperature response (e.g. changes in surface roughness, other atmospheric feedbacks). Nevertheless, the fact that a large part of the variance can be explained by this simple linear model is an indication of the essential role of these selected processes. An exception is the winter season during which a very limited part of the inter-model spread can be explained, suggesting that other processes may play a dominant role. One potential process that could explain differences across RCMs is the occurrence of precipitation feedbacks. We note however that precipitation changes are small in all RCMs with no clear consensus among models (Fig. S5). One possible exception is the summer precipitation decrease in WRFa-NoahMP which could be related to the use of the Grell-Freitas convection scheme (Table 1), while precipitation is less affected in WRFb-NoahMP and WRFb-CLM3.5 which use the Kain-Fritsch scheme. The stronger summer temperature increase in WRFa-NoahMP compared to WRFb-NoahMP and WRFb-CLM3.5 may therefore be linked to this precipitation feedback.

Comparing results from different RCMs sharing either the same LSM or the same atmospheric model can help provide additional insights on the respective role of land versus atmospheric processes. By comparing for instance the temperature response across RCMs (Fig. 1 to 6), it appears, in summer particularly, that the three RCMs based on CCLM (i.e. same atmospheric model with three different LSMs) span almost the full range of RCM responses while CCLM-CLM4.5 and RegCM-CLM4.5 (i.e. same LSM and different atmospheric models) have generally similar patterns of change. This suggests that the summer temperature response to forestation is conditioned primarily by land processes representation more than by atmospheric processes. To quantify objectively the level of similarity or dissimilarity between different RCMs, we compute the Euclidean distance across latitude and longitude between each RCM pairs for each season for differences in 2-meter temperature and precipitation. This distance matrix is then used as a basis for a hierarchical clustering applying the Ward's clustering criterion (Ward 1963). For the 2-meter temperature response, the cluster analysis indicates a relatively high degree of similarity in winter between RCMs sharing the same atmospheric scheme, as illustrated in particular by the clustering of CCLM-TERRA and CCLM-CLM4.5 and of WRFb-NoahMP and WRFb-CLM3.5 (Fig. 13). In contrast, CCLM-TERRA and CCLM-CLM4.5 are relatively far apart in summer suggesting a stronger influence of land processes during this season. This tendency however does not arise in the WRF-based RCMs, with WRFb-NoahMP and WRFb-CLM3.5 showing a high degree of similarity even in summer. A possible explanation could be that NoahMP and CLM3.5 are structurally less different than TERRA and CLM4.5.

4 Discussion and Conclusions

Results from nine RCMs show that, compared to grassland, forests implies warmer temperatures in winter and spring over Northern Europe. This result is robust across RCMs and is a direct consequence of the lower albedo of forests which is the dominating factor during these seasons. In summer and autumn, however, the RCMs disagree on the direction of changes, with responses ranging from a widespread cooling to a widespread warming above 2 degrees in both cases. Although albedo change plays an important role in all seasons by increasing absorbed surface radiation, in summer inter-model differences in the temperature response are to a large extent induced by differences in EF. These conclusions are overall consistent with previous studies based on global climate models. Results from the LUCID and the CMIP5 model intercomparisons have indeed highlighted a robust, albedo-induced, winter cooling effect due to past deforestation at mid-latitudes (Lejeune et al. 2017), in other words implying a winter warming effect of forestation. On the other hand, no robust summer response has been identified in these intercomparisons, mainly attributed to a lack of agreement across models concerning evapotranspiration changes (De Noblet-Ducoudré et al. 2012; Lejeune et al. 2017, 2018).

Resolving this lack of consensus will require intensified efforts to confront models and observations and identify possible model deficiencies (Meier et al. 2018; Duveiller et al. 2018a; Boisier et al. 2013, 2014). For instance, a key feature emerging from observation-based studies is the fact that mid-latitude forests are colder during the day and warmer during the night compared to grassland (Lee et al. 2011; Li et al. 2015; Duveiller et al. 2018b). It is striking that none of the LUCID and CMIP5 models reflect this diurnal behavior (Lejeune et al. 2017), nor do the RCMs analyzed in this study (i.e. a majority of RCMs have a diurnal signal opposite to observations, two other RCMs indicate a cooling effect of forests for both day and night, one exhibit a warming effect for both day and night). It is however important to note that this apparent contradiction may not be only attributable to model deficiencies and could be in part related to discrepancies in the scale of processes considered in models and observations. Indeed, observation-based estimates capture mainly local changes in surface energy balance and temperature due to land cover and are unlikely to reflect the type of large scale atmospheric feedbacks triggered in coupled climate models (especially given the large scale nature of the forest expansion considered in our experiments). Similarly, the fact that a majority of RCMs simulate a summer decrease in evapotranspiration over many regions following forestation is at odds with current observational evidence (Chen et al. 2018; Meier et al. 2018; Duveiller et al. 2018b) and might play a role in the simulated summer daytime warming in most RCMs. Although the reasons behind this behaviour may be model-specific, some recent work based on the CLM4.5 model, which is used in two of the RCMs here, sheds some light on the possible processes involved (Meier et al. 2018). It was found that while evapotranspiration is higher in spring under forested conditions in CLM4.5, trees become more water stressed than grassland in summer (even under equivalent soil moisture conditions) in particular due to unrealistic choices of root distribution, photosynthetic parameters and water uptake formulation. After improvement of these aspects in CLM4.5, evapotranspiration was found to be more realistically simulated resulting also in an improved daytime temperature difference between grassland and forest (Meier et al. 2018). An important insight from this first phase of RCM experiments is therefore that a particular attention should be given to model evaluation and benchmarking in future phases of the LUCAS initiative.

An additional insight from this study concerns the role of land versus atmospheric processes. Some of the participating RCMs share the same atmospheric scheme (i.e. same version and configuration) but are coupled to different land surface models, or share the same land surface model in combination with different atmospheric schemes. This represents a unique opportunity to objectively determine the origin of uncertainties in the simulated response. For instance, we find that land processes representation is heavily involved in the large model spread in summer temperature response. The range of responses generated by using three different LSMs within the same atmospheric scheme (CCLM) is almost as large as the full model range in summer. Supporting this conclusion, a simple regression-based analysis shows that, except in winter, changes in albedo and EF can explain most of the inter-model spread in temperature sensitivity, in other words indicating that land processes primarily determine the simulated temperature response. Atmospheric processes can nevertheless also play a substantial or even dominant role for example in winter or for other variables such as precipitation.

In this first phase of LUCAS, we relied on idealised experiments at relatively low resolution (50 km) to gain insights on the biogeophysical role of forests across a range of European climates. Future phases of LUCAS will evolve toward increasing realism for instance by 1) investigating transient historical LUC forcing as well as RCP-based LUC scenarios, 2) considering a range of land use transitions beyond grassland to forest conversion and 3) assessing the added-value of higher (kilometre-scale) resolution when assessing local LUC impacts. Finally, the most societally-relevant adverse effects or benefits from land management strategies may become apparent only when addressing changes in extreme events such as heatwaves or droughts (Davin et al. 2014; Lejeune et al. 2018), an aspect which will receive more attention in future analyses based on LUCAS simulations.

Data availability

The data and scripts used are available upon request from the corresponding author.

Author contribution

ELD, DR, MB, RMC, EC, PH, LJ, EK, KR, MR, PMMS, GS, SS, GS, MHT and KW-S performed the RCM simulations, using vegetation maps produced by ELD. ELD designed the research, analysed the data and wrote the manuscript. All authors contributed to interpreting the results and revising the text.

Competing Interests

The authors declare that they have no conflict of interests.

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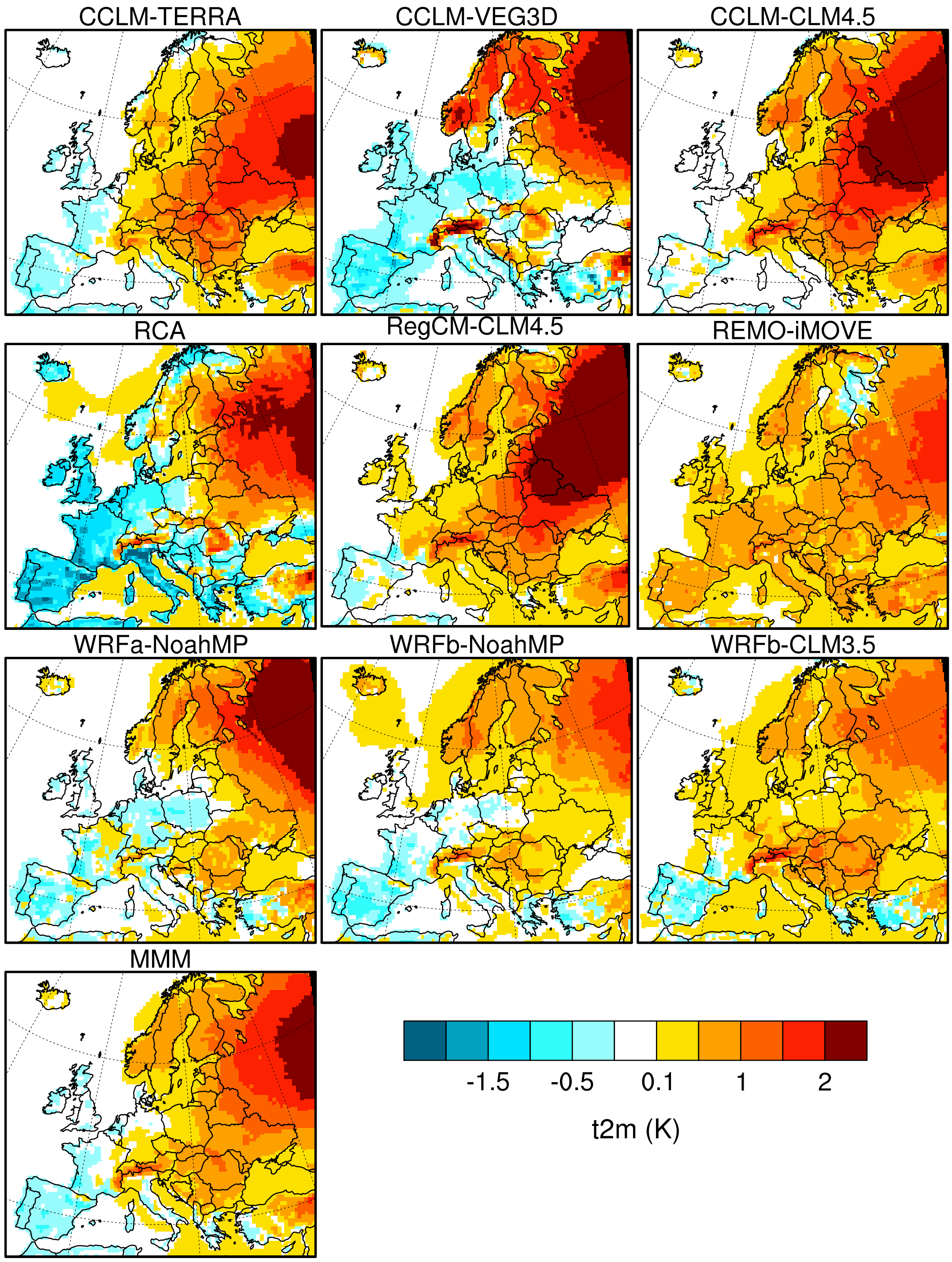

Figure 1: Seasonally-averaged 2-meter temperature (FOREST minus GRASS) for winter (DJF).

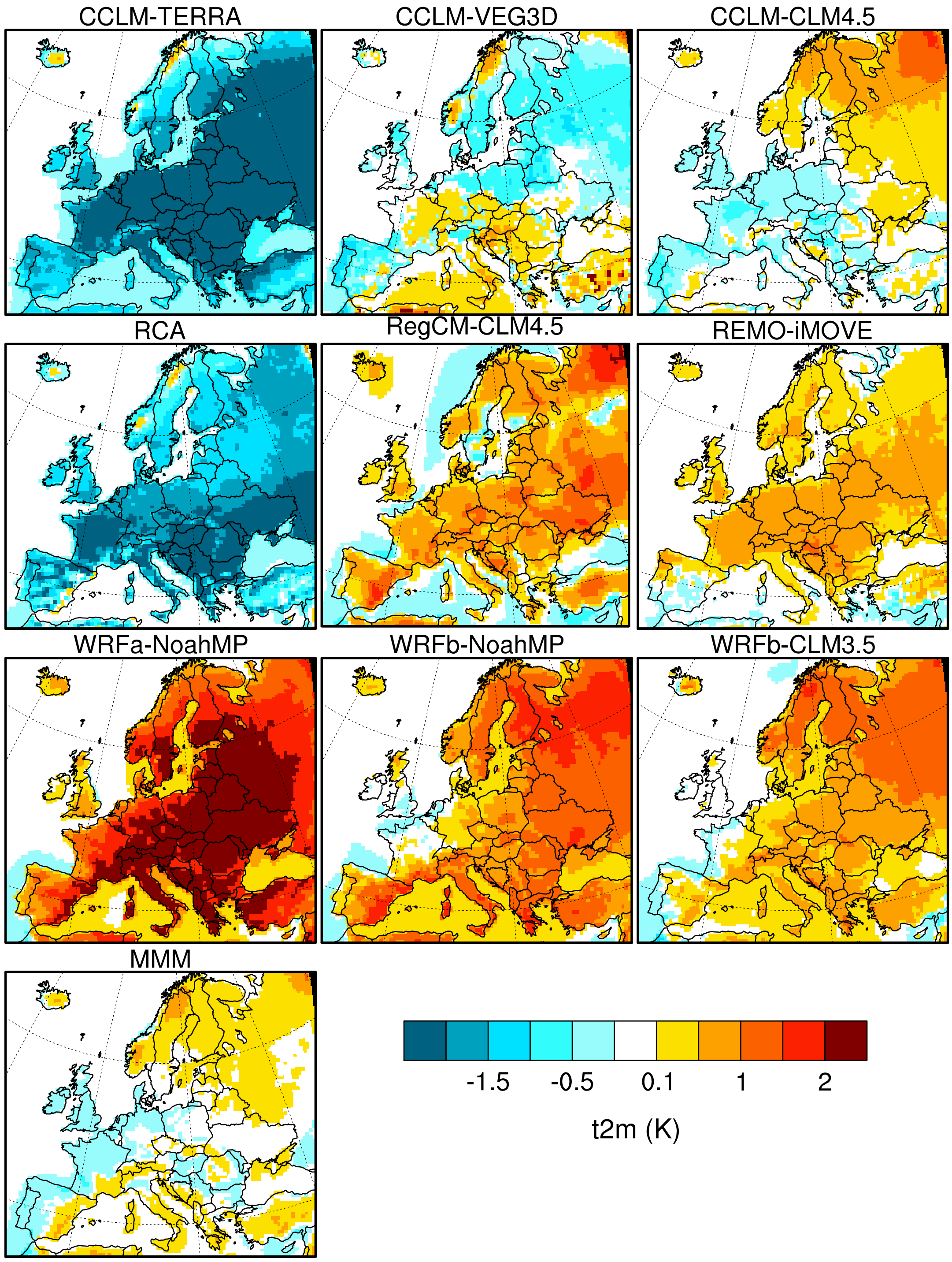

Figure 2: Seasonally-averaged 2-meter temperature (FOREST minus GRASS) for summer (JJA).

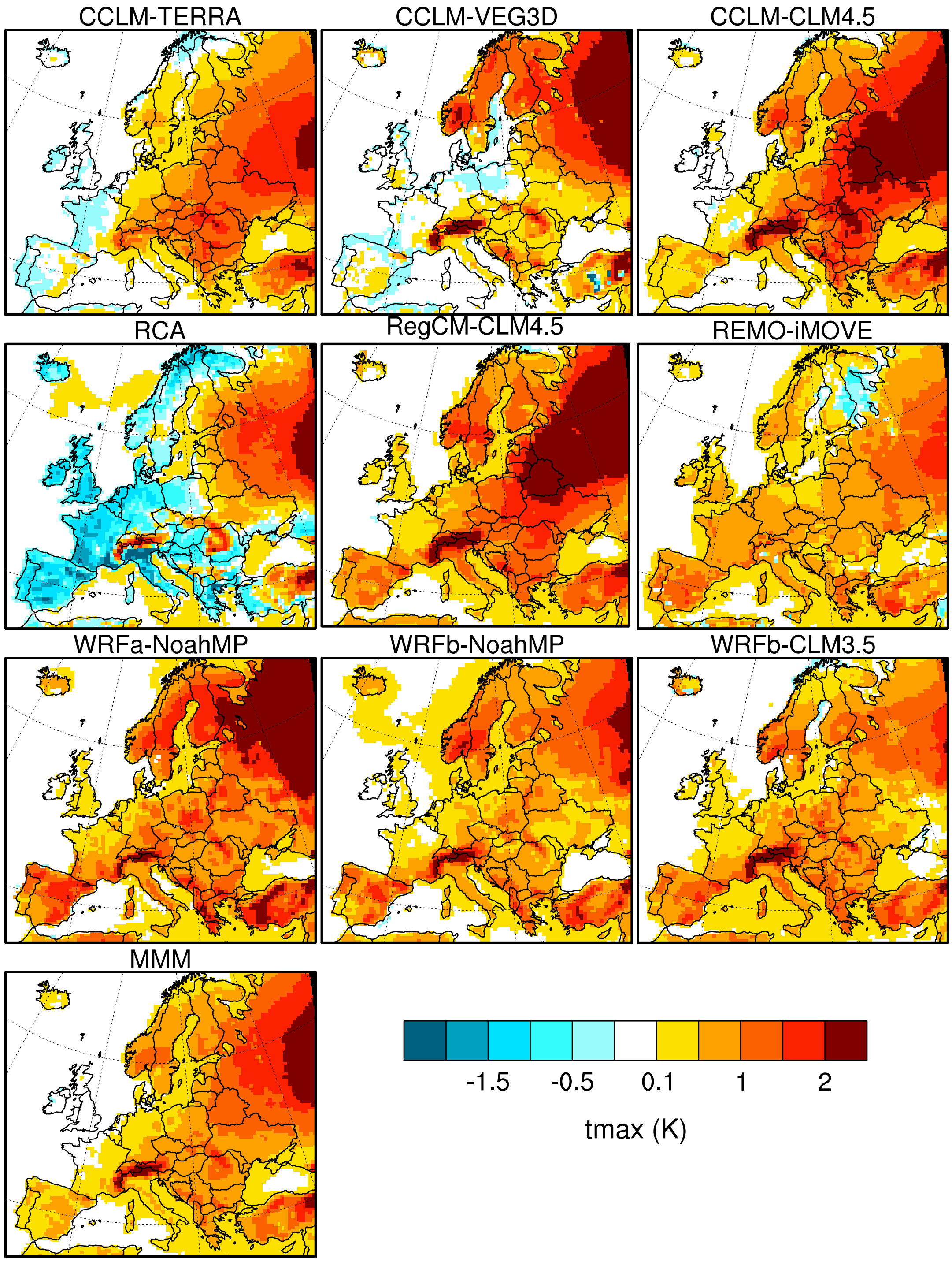

Figure 3: Seasonally-averaged daily maximum 2-meter temperature (FOREST minus GRASS) for winter (DJF).

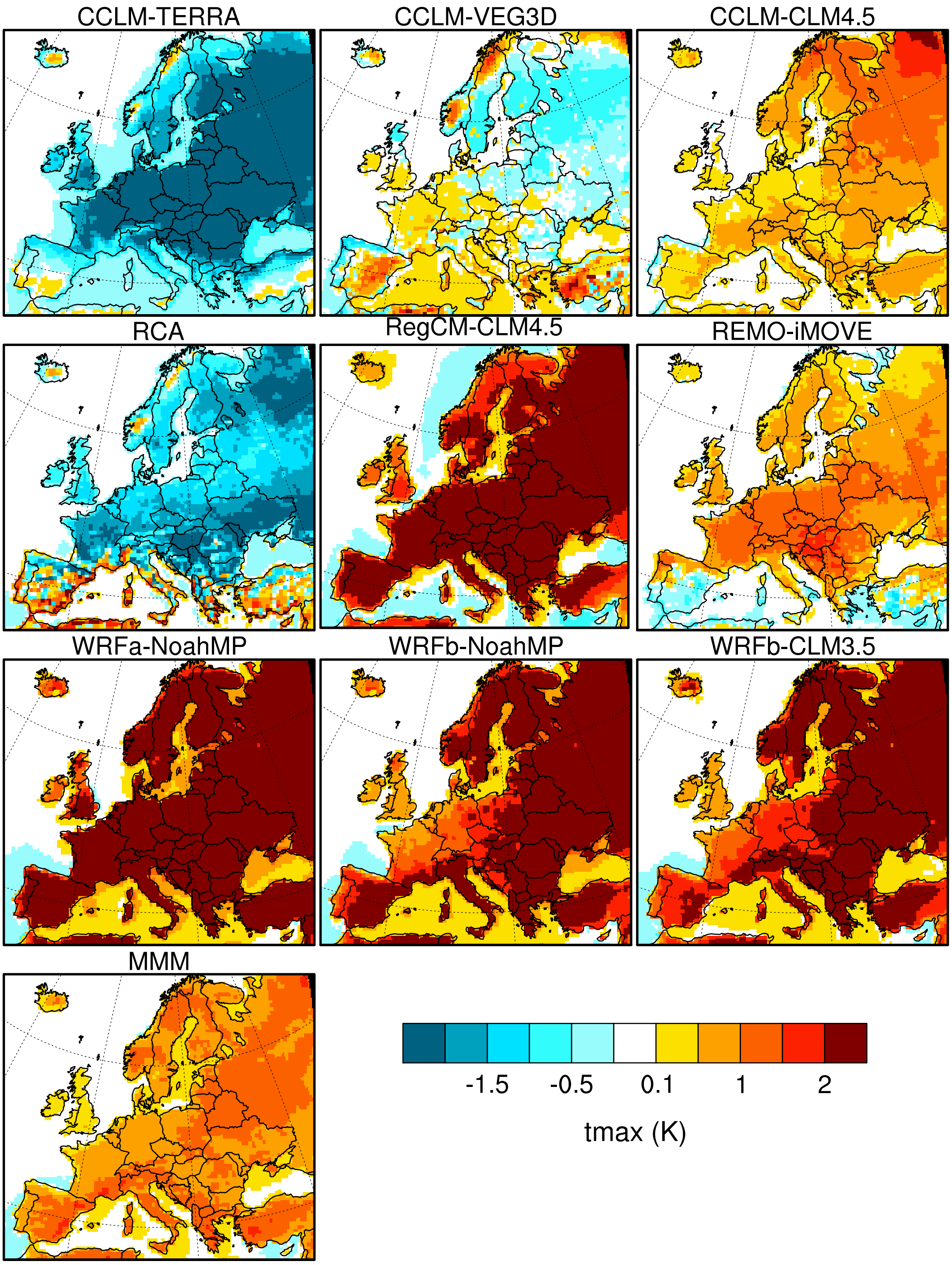

Figure 4: Seasonally-averaged daily maximum 2-meter temperature (FOREST minus GRASS) for summer (JJA).

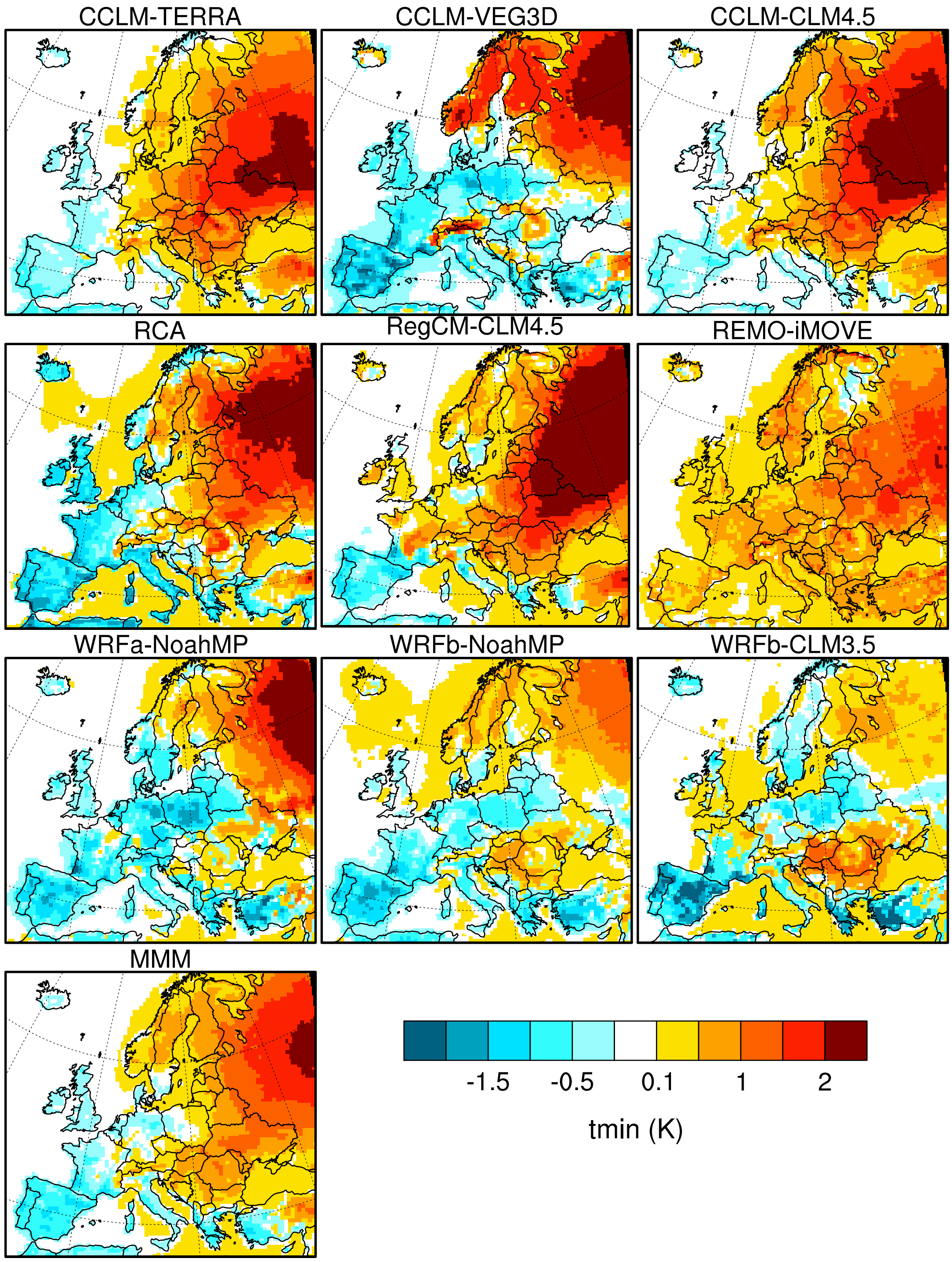

Figure 5: Seasonally-averaged daily minimum 2-meter temperature (FOREST minus GRASS) for winter (DJF).

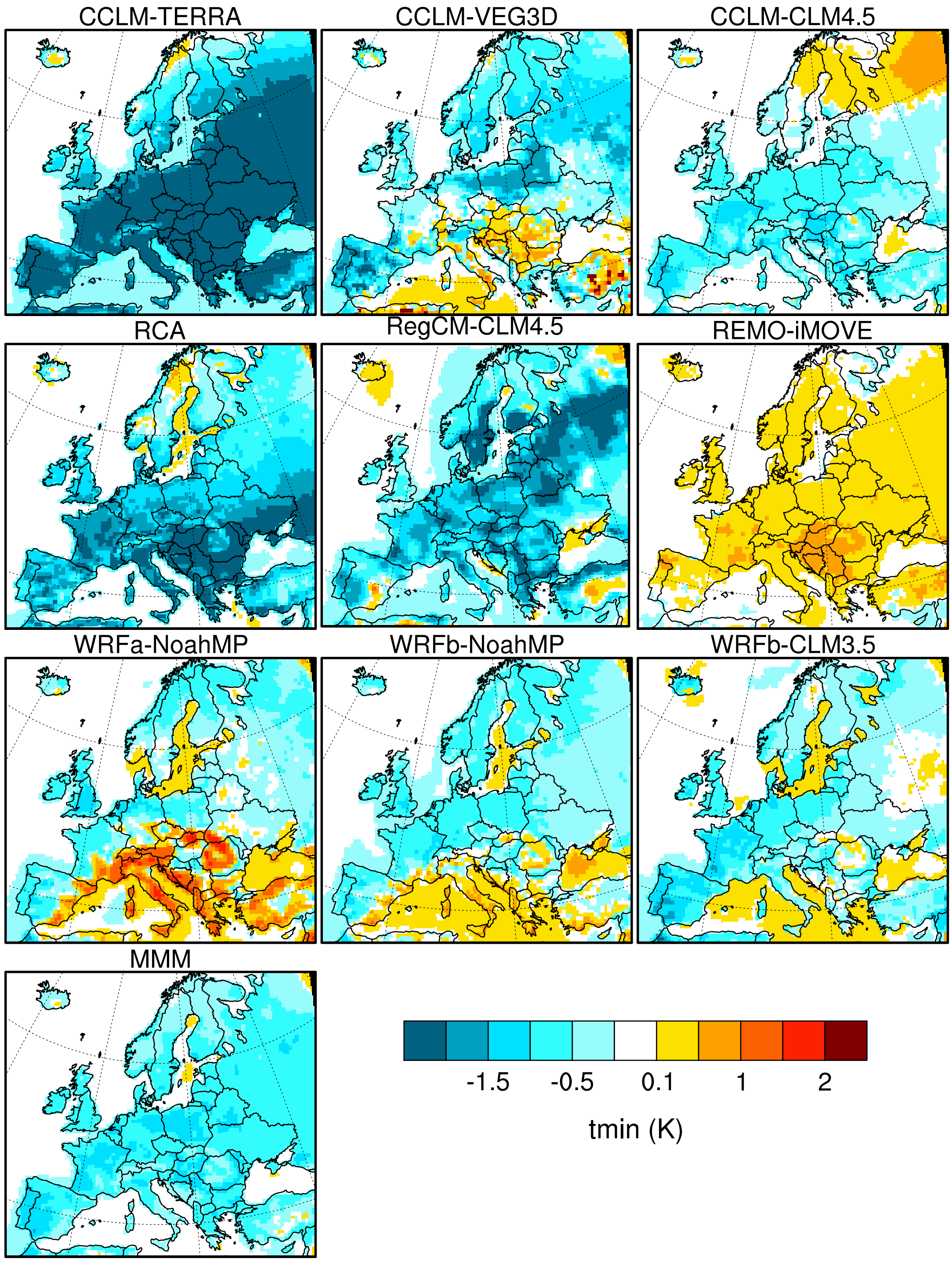

Figure 6: Seasonally-averaged daily minimum 2-meter temperature (FOREST minus GRASS) for summer (JJA).

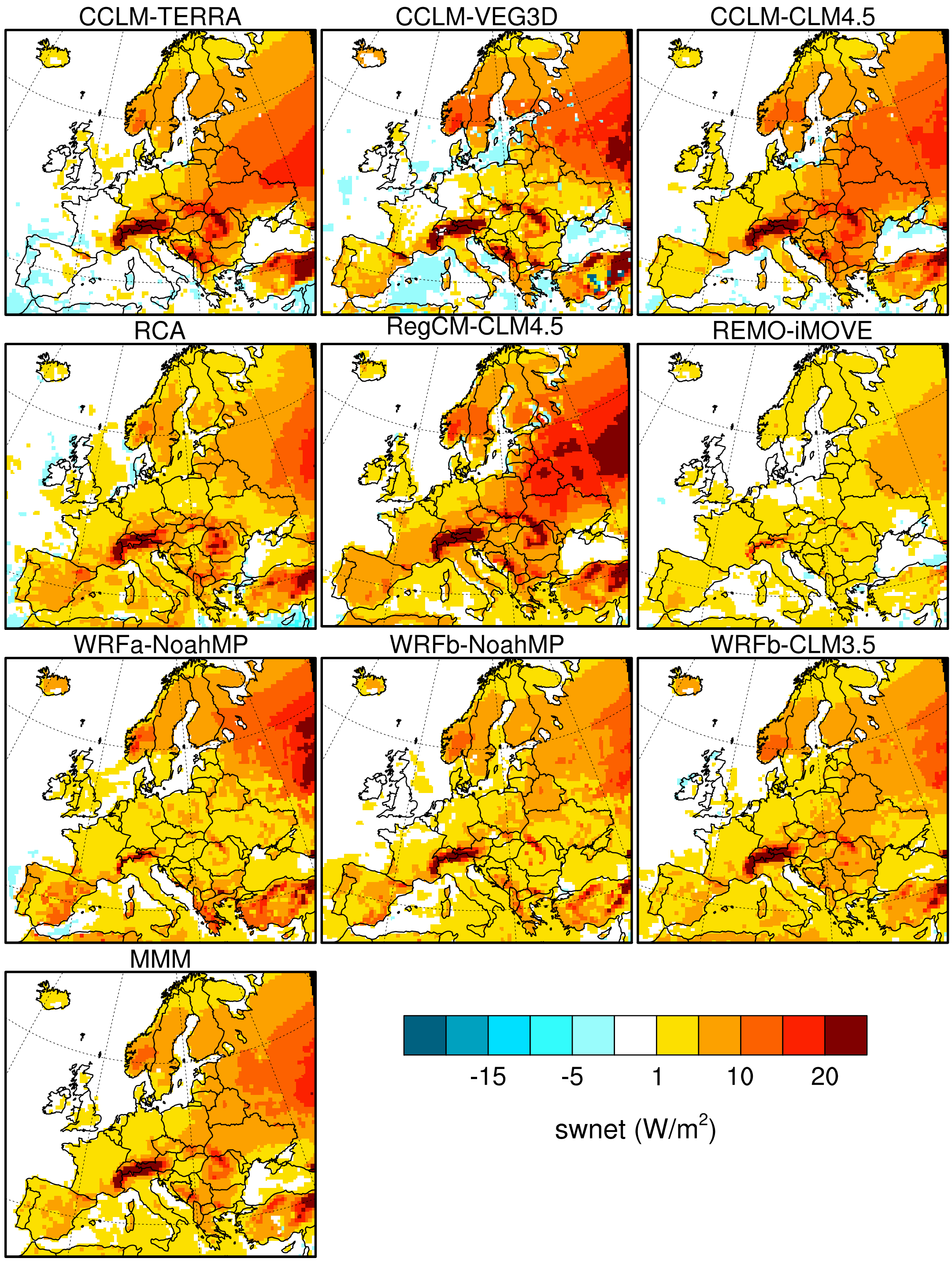

Figure 7: Seasonally-averaged net surface shortwave radiation (FOREST minus GRASS) for winter (DJF).

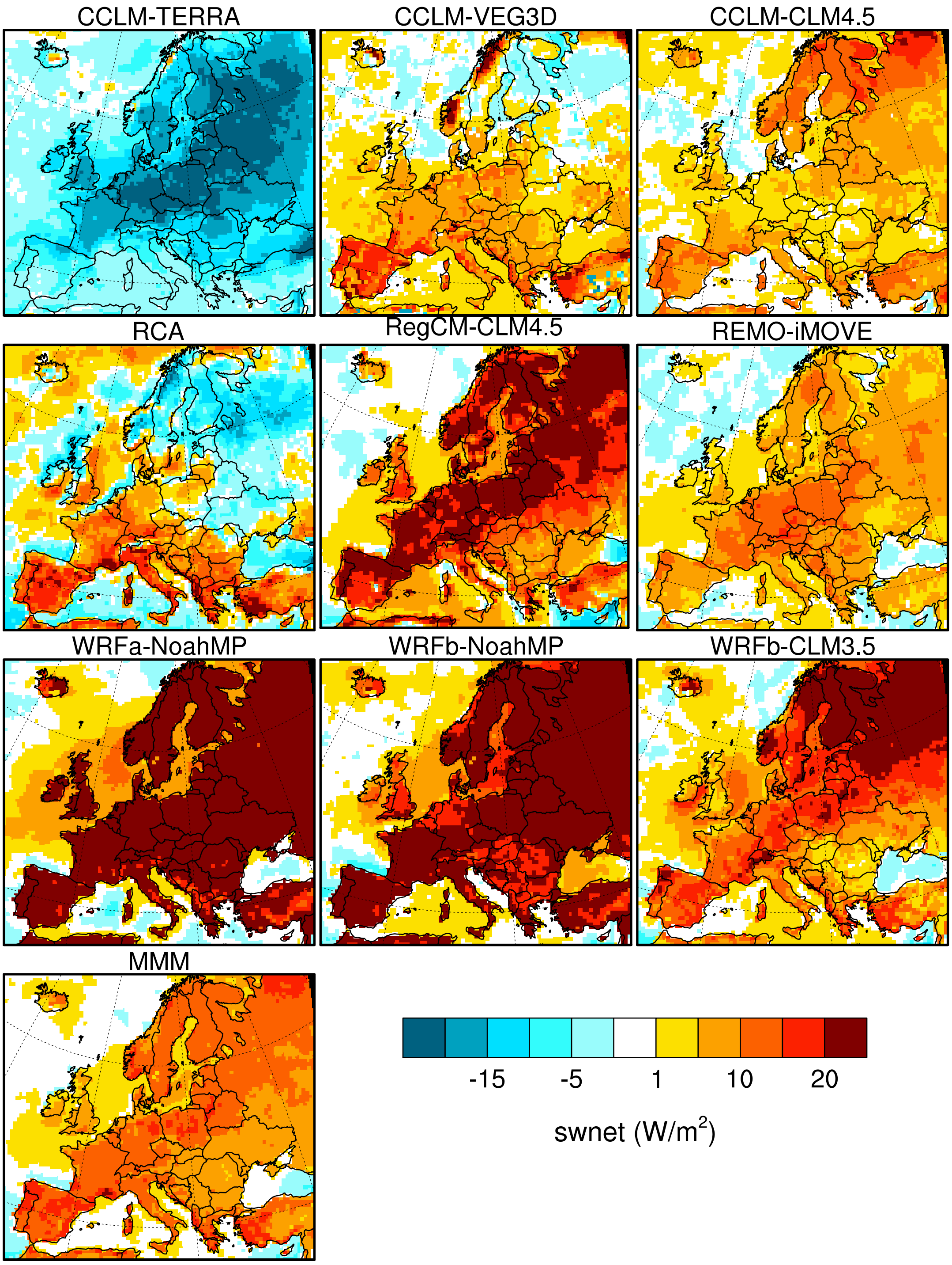

Figure 8: Seasonally-averaged net surface shortwave radiation (FOREST minus GRASS) for summer (JJA).

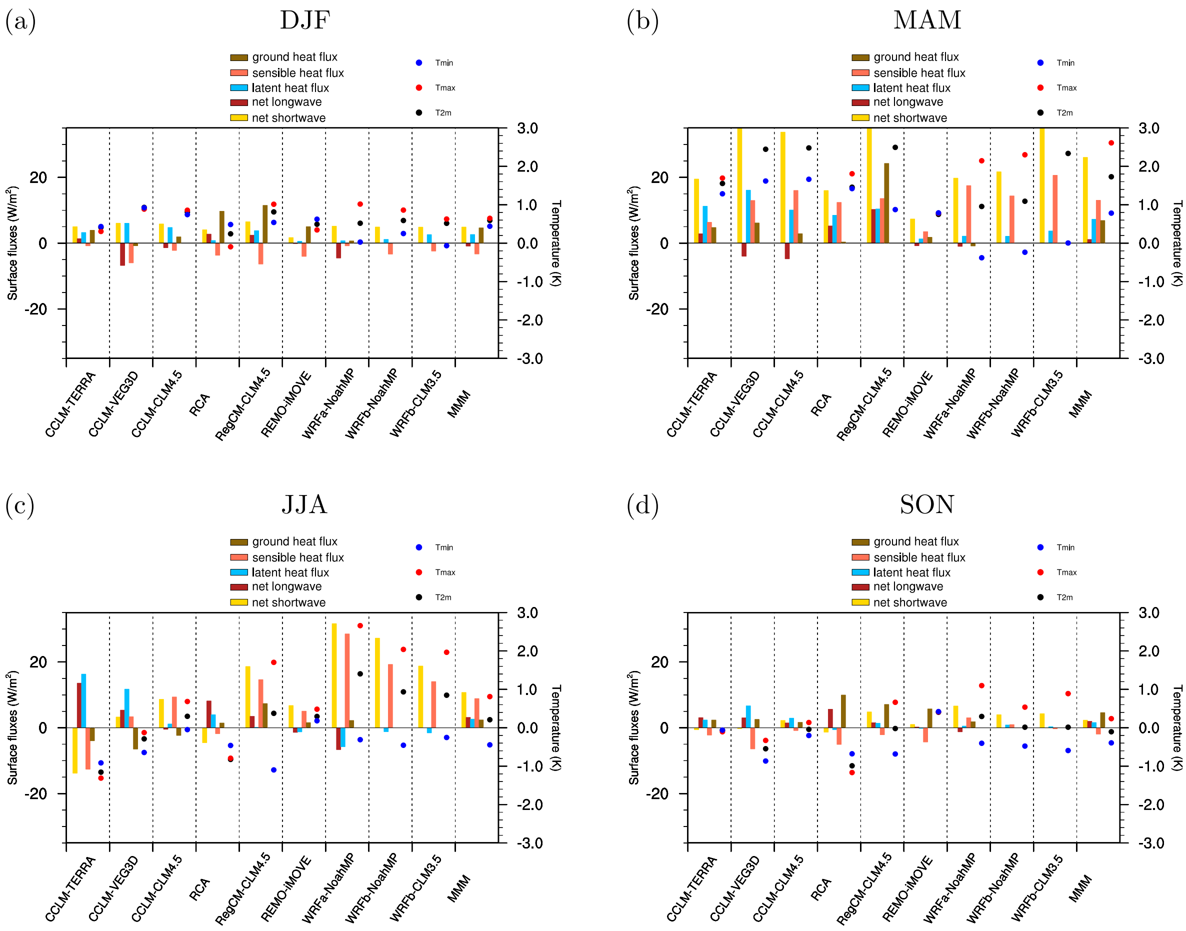

Figure 9: Changes in temperature and in surface energy balance components (FOREST minus GRASS) averaged over Scandinavia for DJF, MAM, JJA and SON. Results for other regions are shown in the Supplementary Information.

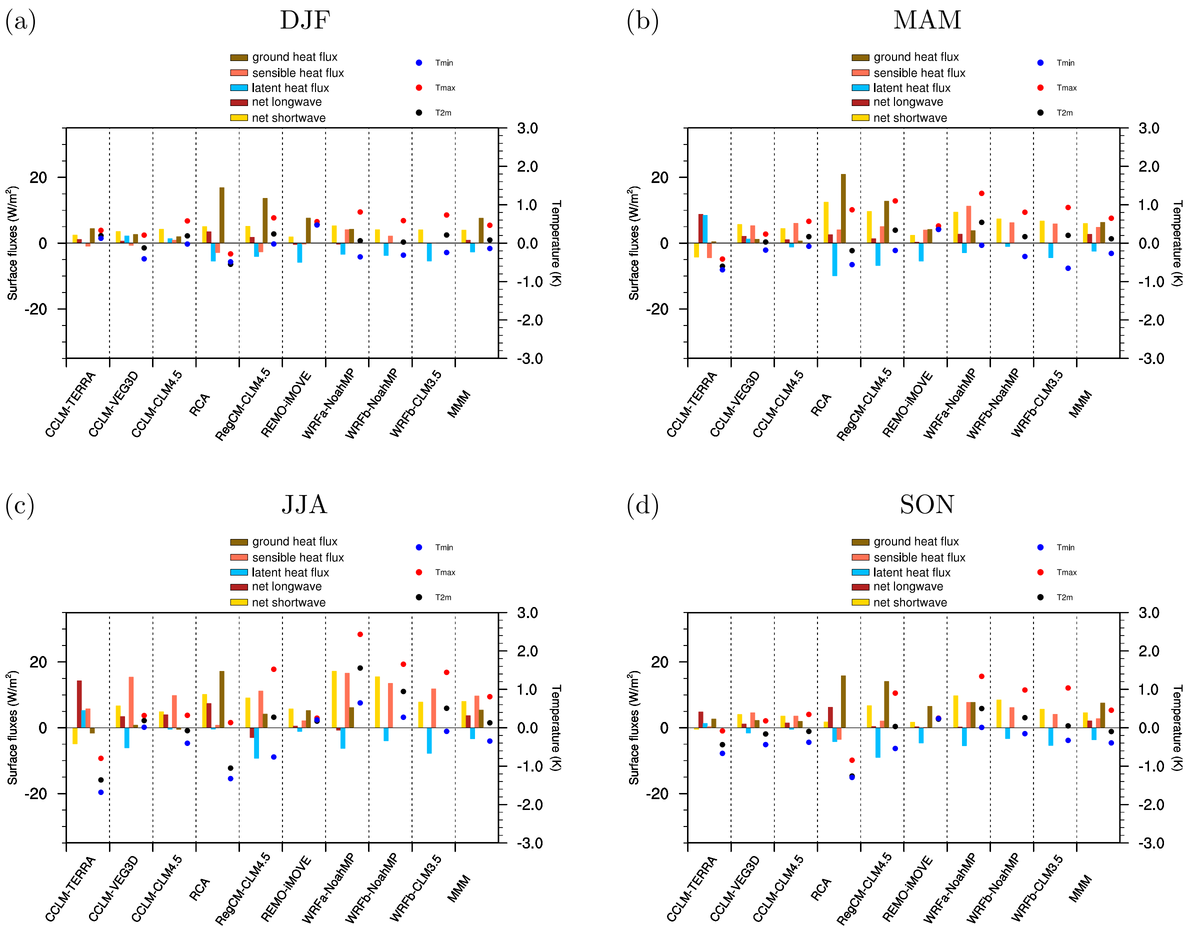

Figure 10: Changes in temperature and in surface energy balance components (FOREST minus GRASS) averaged over the Mediterranean for DJF, MAM, JJA and SON. Results for other regions are shown in the Supplementary Information.

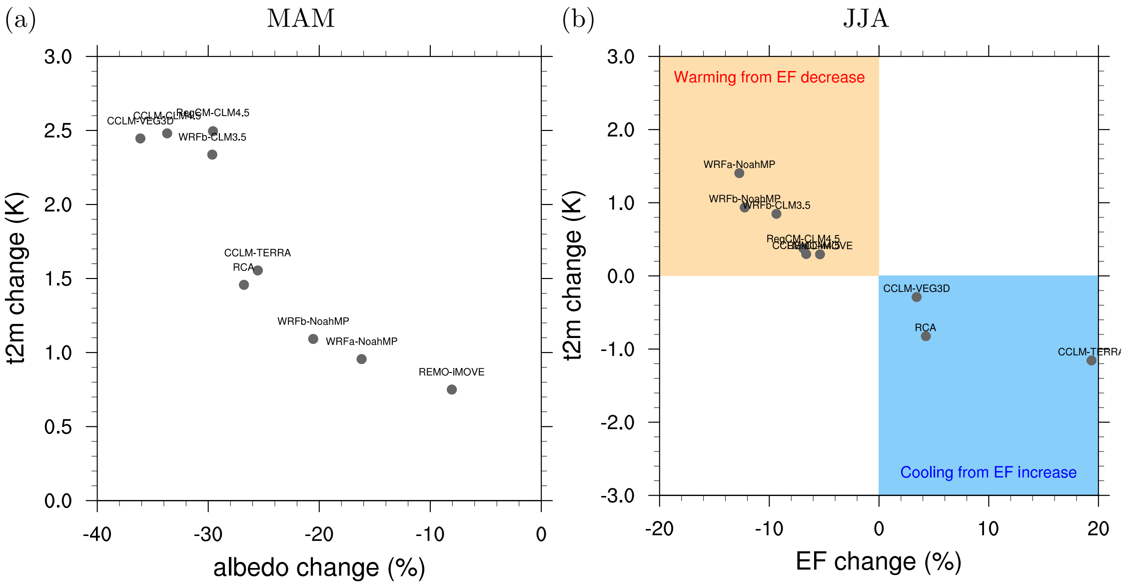

Figure 11: Illustrative relationships between changes (FOREST minus GRASS) in 2-meter temperature and albedo in spring (a) and between changes in 2-meter temperature and EF (evaporative fraction) in summer (b) for Scandinavia.

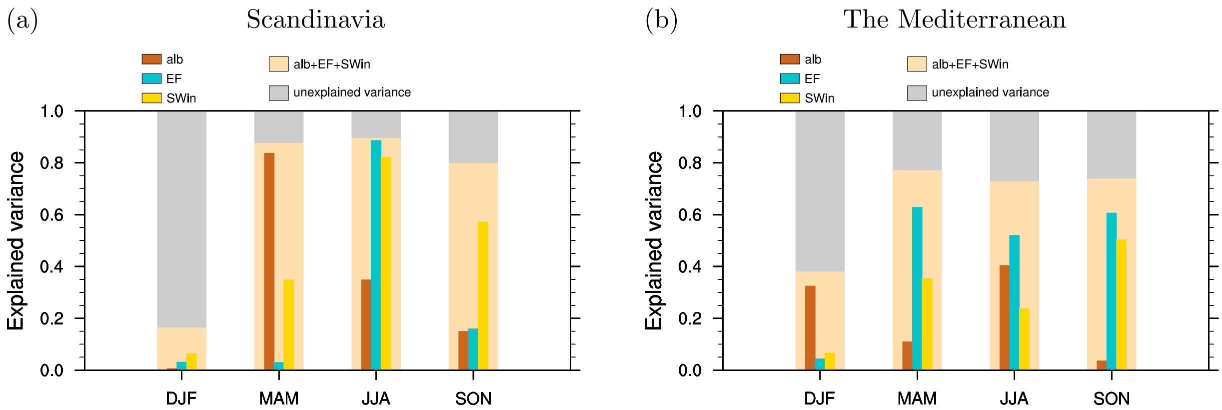

Figure 12: Fraction of inter-model variance in 2-meter temperature change (FOREST minus GRASS) explained by changes in albedo, evaporative fraction, incoming surface shortwave radiation or the three combined. Alb: inter-model correlation (Rsquared) between changes in albedo and 2-meter temperature. EF: inter-model correlation (Rsquared) between changes in evaporative fraction and 2-meter temperature. SWin: inter-model correlation (Rsquared) between changes in incoming surface shortwave radiation and 2-meter temperature. Alb+EF+SWin: Rsquared of a multi-linear regression combining the three predictors. Results for other regions are shown in the Supplementary Information.

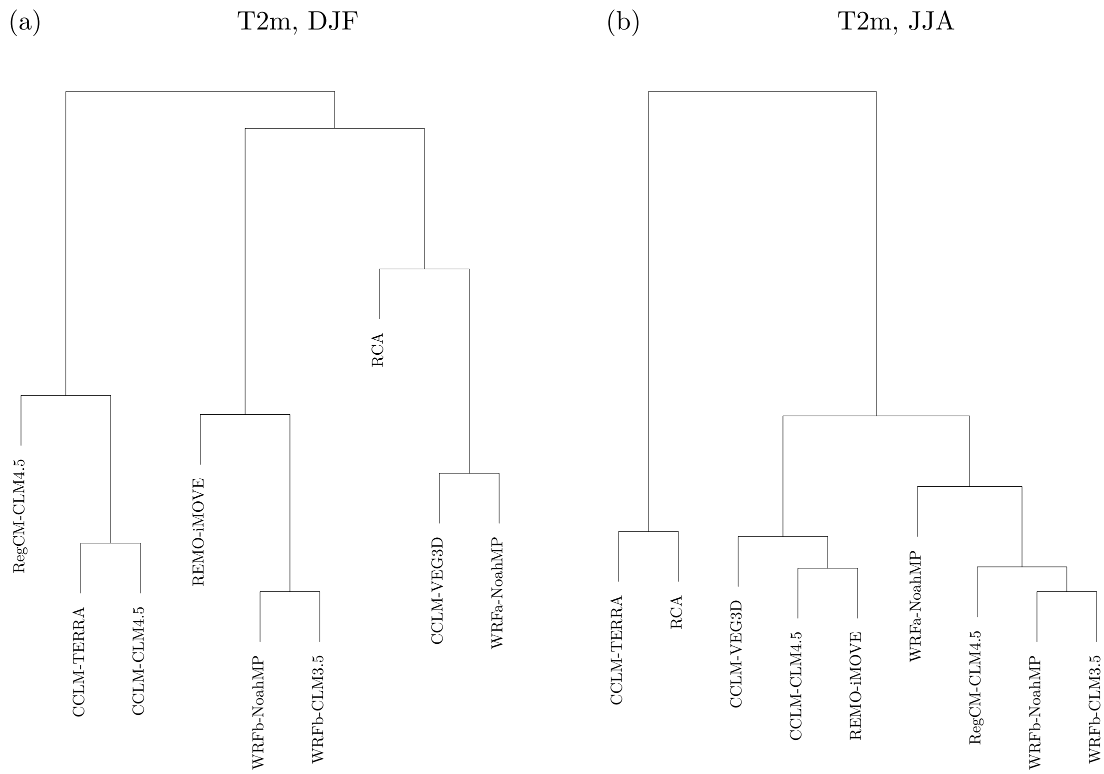

Figure 13: Dendrogram of the clustering analysis based on the 2-meter temperature response (FOREST minus GRASS) for DJF and JJA. The underlying distance matrix between RCM pairs is based on the Euclidean distance across latitude and longitude for the given season.