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Key Points:

- New five-layer soil-hydrology scheme improves seasonal prediction of European summer temperatures
- Improvements likely due to more realistic land-atmosphere coupling and large-scale circulation
- Hindcast skill significantly higher for more recent years compared to earlier years

Supporting Information:

- Supporting Information S1

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Improved Seasonal Prediction of European Summer Temperatures With New Five-Layer Soil-Hydrology Scheme

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Abstract We evaluate the impact of a new five-layer soil-hydrology scheme on seasonal hindcast skill of 2 m temperatures over Europe obtained with the Max Planck Institute Earth System Model (MPI-ESM). Assimilation experiments from 1981 to 2010 and 10-member seasonal hindcasts initialized on 1 May each year are performed with MPI-ESM in two soil configurations, one using a bucket scheme and one a new five-layer soil-hydrology scheme. We find the seasonal hindcast skill for European summer temperatures to improve with the five-layer scheme compared to the bucket scheme and investigate possible causes for these improvements. First, improved indirect soil moisture assimilation allows for enhanced soil moisture-temperature feedbacks in the hindcasts. Additionally, this leads to improved prediction of anomalies in the 500 hPa geopotential height surface, reflecting more realistic atmospheric circulation patterns over Europe.

1. Introduction

In the past decades European summer temperature anomalies have impacted human society in many ways. During heat waves, such as in summer 2003, an extraordinarily large number of heat-related deaths was reported in central Europe (Hémon & Jougla, 2004); crop failure and forest fires have led to severe financial losses and damages of the environment (Heck et al., 2004). However, state-of-the-art coupled climate models show only moderate skill in predicting European summer temperature anomalies and extreme cases such as the summer 2003 (e.g., Weisheimer et al., 2011). Among the many contributing effects, previous studies showed that land-atmosphere coupling in particular plays an important role for amplifying summer climate conditions (Seneviratne et al., 2010), and improvements in the representation of land-surface uncertainty can affect the forecast skill of predictions of European summer conditions (MacLeod et al., 2016). Here we use the Max Planck Institute Earth System Model (MPI-ESM, Giorgetta et al., 2013) with the newly developed five-layer soil-hydrology scheme (Hagemann & Stacke, 2015) and examine the impact of the improved soil representation on the hindcast skill of European summer temperatures.

The variability of European surface climate is controlled by a combination of mechanisms, comprising land-atmosphere coupling (Fischer et al., 2007), large-scale atmospheric circulation patterns such as the occurrence of blocking regimes (Reinhold & Pierrehumbert, 1982), and teleconnections with other variability modes of the Earth System (e.g., Behera et al., 2013; Saeed et al., 2014). In land-atmosphere coupling soil moisture is a crucial variable, as it partitions the incoming radiative energy into latent and sensible heat fluxes and, thus, invokes a soil moisture-temperature feedback (Seneviratne et al., 2010). This mechanism distinguishes two soil states, a dry state where evapotranspiration is limited by the available soil moisture, and a wet state where evapotranspiration is limited by the available energy. In the wet state, the dissipation of incoming energy into latent heat fluxes leads to a dampening of surface warming. In the dry state, less evaporation allows for more energy being available for surface warming and, thus, increased sensible heat fluxes.

In order to account for a more realistic soil moisture-temperature feedback, soil moisture was incorporated in the initialization of seasonal prediction experiments in recent studies. Some studies, such as the Global Land-Atmosphere Coupling Experiment Intercomparison Project, did not find a significant improvement of seasonal temperature predictions over Europe (Koster et al., 2011). Other recent studies, however, found significant improvements at least in some regions of Europe (Ardilouze et al., 2017; Prodhomme et al., 2016). For instance, Prodhomme et al. (2016) found the 2010 Russian heat wave to be predictable only with realistic soil moisture initialization, but the predictability of the 2003 European heat wave did not improve with soil moisture initialization. Other studies suggest that the origin of the 2003 heat wave rather lies in the large-scale pattern of atmospheric circulation (e.g., Black et al., 2004).

Previous studies on the impact of land-atmosphere coupling on the seasonal hindcast skill of European summer temperatures were based on different models, each using its own soil scheme. While simple bucket soil schemes capture relatively well the soil moisture limitation on evapotranspiration in climate models, they yield deficiencies in the limitation of the plants' transpiration (Seneviratne et al., 2010) and, thus, cause an overestimation of evapotranspiration compared to other soil schemes (Henderson-Sellers et al., 1996). Additionally, the soil moisture data set used for model initialization varies among studies. While some studies (e.g., Douville, 2010) use a soil moisture climatology compiled from sparse observational data (Dirmeyer et al., 2002), other studies (e.g., Prodhomme et al., 2016) use European Centre for Medium-Range Weather Forecast (ECMWF) Re-Analysis Land (ERA-Land) data (Balsamo et al., 2015).

In this study, we evaluate the seasonal hindcast skill in two sets of 10-member seasonal hindcast experiments performed with MPI-ESM using the same initialization setup and model configuration but different soil schemes. For one hindcast set the MPI-ESM bucket soil scheme (Roeckner et al., 2003) is used; for the other set the new five-layer soil-hydrology scheme (Hagemann & Stacke, 2015) is used. Both hindcast sets are initialized from fully coupled assimilation experiments performed with the respective soil setup. In these experiments different atmospheric and oceanic variables are nudged, but no direct assimilation of soil moisture data is performed. We find significant seasonal hindcast skill for summer temperatures over large parts of the European continent only if the five-layer soil-hydrology scheme is switched on. In this configuration MPI-ESM already showed significant hindcast skill for European summer temperatures comparable to other model systems evaluated within a multimodel study for the period 1992–2010 (Ardilouze et al., 2017). To investigate the exact cause for the improved skill obtained with the five-layer scheme, we evaluate here in both hindcast sets the direct impact of land-atmosphere coupling on temperature predictions, and possible indirect skill improvements through improved predictions of anomalies in the 500 hPa geopotential height, the "steering" level of synoptic features (e.g., Carlson, 1991), such as atmospheric blocking regimes (Scherrer et al., 2006). Additionally, we evaluate a longer time period (1981–2010) and show that significant hindcast skill for European summer temperatures is only obtained for the second half of this period.

2. Model Description and Experimental Setup

All simulations analyzed in this study were performed with the MPI-ESM seasonal prediction system (Baehr et al., 2015). MPI-ESM was used in its low-resolution configuration (MPI-ESM-LR) where the atmosphere component ECHAM6 has a horizontal resolution of T63 ($\sim$1.9° $\times$ 1.9°) and 47 levels between the surface and 0.01 hPa (Stevens et al., 2013). The atmospheric mean state and variability are realistically simulated in this setup (Stevens et al., 2013). The soil scheme is implemented in the land-surface model JSBACH, a subcomponent of ECHAM6 (Raddatz et al., 2007). The bucket soil scheme is described in Roeckner et al. (2003); the new five-layer soil-hydrology scheme is described in Hagemann and Stacke (2015). With the new five-layer scheme not all of the water in a grid cell is available for plants' transpiration, since water can be stored below the root zone. Soil moisture anomalies and memory are both simulated more appropriately with the five-layer soil scheme (Stacke & Hagemann, 2016). Its level of complexity is similar to other multilayer soil schemes, for example, H-TESSEL (Balsamo et al., 2009) or SECHIBA (Guimberteau et al., 2014). It explicitly simulates gravitational drainage and soil water diffusion between the separate layers and accounts for spatial heterogeneity of soil parameters (Hagemann & Stacke, 2015).

The ocean component of MPI-ESM is the Max Planck Institute Ocean Model (MPIOM), which in the applied configuration has a nominal resolution of 1.5° with poles located in South Greenland and in Antarctica (Jungclaus et al., 2013). This corresponds with a horizontal resolution of 15 km near Greenland and 185 km in the tropical Pacific. In the vertical, the ocean is resolved with 40 levels. The distance between the centers of two levels ranges from 10 to 250 m. The sea ice component of MPIOM consists of a dynamic/thermodynamic sea-ice model based on Hibler (1979).

The two assimilation experiments, differing only in the employed soil setup, cover the period 1979–2010. They are started from a climate state which has undergone a 1,000 year preindustrial control simulation followed by a historical simulation forced with increasing greenhouse gas concentrations from 1860 to 1979. The applied assimilation technique is Newtonian relaxation (or "nudging"). Atmospheric and oceanic reanalyses and observations are nudged into the model using full-field data assimilation in all atmospheric and oceanic levels. In order to cover the main sources of predictability we carefully select variables and associated relaxation times for assimilating the observed state of the Earth System into the model. In the atmosphere, different relaxation times are used for assimilation of vorticity (6 h), divergence (2 days), temperature (1 day), and surface pressure (1 day), while salinity and temperature in the ocean are nudged with a relaxation time of 10 days. For assimilation of atmospheric quantities, the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analyses ERA-Interim (Dee et al., 2011) is used. Assimilating its dry thermodynamic variables causes an indirect assimilation of soil moisture. In the ocean model component, temperature and salinity are nudged toward Ocean Re-Analysis System 4 data (Balmaseda et al., 2013). Sea-ice concentrations from the National Snow and Ice Data Center Bootstrap data set (Comiso, 2000) are assimilated into the model with an effective relaxation time of 20 days (Tietsche et al., 2013). Relaxation times differ among model components according to the different response times of the components.

A 10-member ensemble of 6 month hindcast simulations is started every year on 1 May from each of the two assimilation experiments. Ensemble members are generated by small disturbances of oceanic and atmospheric states. Bred vectors are used to add small disturbances to the global three-dimensional ocean temperature and salinity fields (Baehr & Piontek, 2014), and the diffusion is slightly disturbed in the uppermost model layer at 0.01 hPa.

In the following, the hindcast skill for European summer temperatures is evaluated. It is computed from ensemble means of the two hindcast sets with ERA-Interim (Dee et al., 2011) used as reference data.

3. Hindcast Skill for European Summer Temperatures

We compare the hindcast skill obtained for European 2 m summer temperature from the two hindcast sets performed with MPI-ESM using the bucket soil scheme and the five-layer soil-hydrology scheme, respectively. The anomaly correlation coefficient (ACC, e.g., Siegert et al., 2017, equation (1)) between simulated and reanalyzed European June-July-August (JJA) mean 2 m air temperatures within 1981–2010 is used as a measure for the hindcast skill in the two hindcast sets.

We find significant skill over large parts of the European continent only when the five-layer soil-hydrology scheme is used (Figures 1a and 1b). While in a few regions, such as Spain, the Alpine region, and western Russia the skill does not change substantially or even shows a slight decrease with increasing complexity of the soil scheme, the hindcast skill improves particularly over France, Great Britain, Scandinavia, and the Balkan region (Figure 1c). This is on the one hand due to the trend of the European 2 m summer temperature which is more realistically simulated with the five-layer soil scheme (Figure 1d). On the other hand, also, extreme events, such as the central and southern European heat wave in 2003, are better predicted with the increased complexity in the soil setup. When ACCs are computed from the detrended time series of 2 m temperatures, regions with significant hindcast skill are limited (Figure S1 in the supporting information). This shows that in order to obtain good hindcast skill, it is important to capture the underlying warming trend in hindcast simulations. While Liniger et al. (2007) showed that the warming trend induced by anthropogenic climate change is lost by up to 70% 2 months after initialization in their seasonal forecast system, we find the trend in European summer temperature to be persistent in the MPI-ESM seasonal prediction system when the five-layer soil scheme is used (Figure 1d).

To investigate the temporal and regional origin of the obtained hindcast skill, we split the 30 year period of hindcast start dates (1981–2010) into an early period (1981–1995) and a late period (1996–2010) and investigate two different regions with large hindcast skill, the Balkans and Scandinavia. These regions were found by Ardilouze et al. (2017) to show high predictive skill in several climate models over the period 1992–2010, and the Balkans were identified as a "hot spot" for soil moisture-atmosphere coupling (Seneviratne et al., 2006). We find no significant skill in any of the two hindcast sets and regions for the early period, while significant skill is obtained with the five-layer soil scheme in all investigated regions in the late period (Table S1). For the entire period significant hindcast skill is found also for the 2 m temperature averaged over the entire

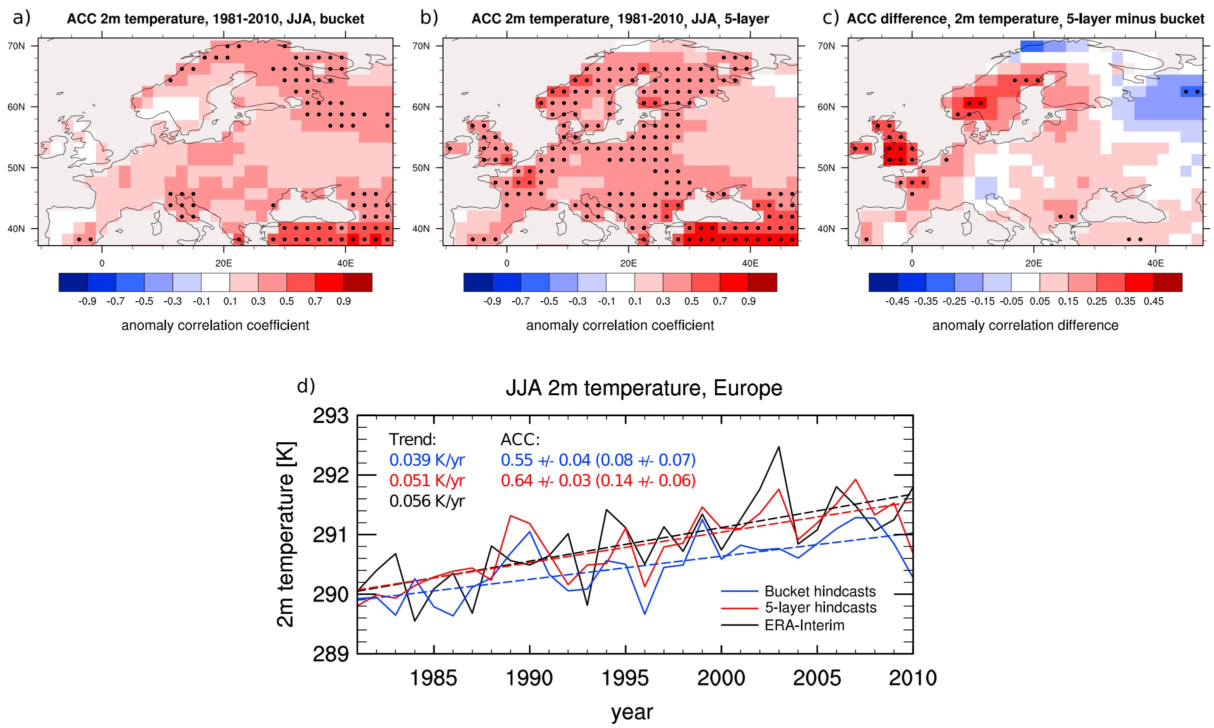

Figure 1. Anomaly correlation coefficients (ACCs) for JJA-mean 2 m temperature over Europe, computed from the ensemble mean of hindcasts using (a) the bucket soil scheme and (b) the five-layer soil-hydrology scheme. ERA-Interim was used as reference data. Dotted regions indicate significant ACCs at the 95% level obtained from a bootstrap significance test (Goddard et al., 2013). (c) The ACC difference is depicted with significance computed after the modified Fisher transformation described by Siegert et al. (2017). (d) Time series of European summer temperature, averaged over all land grid boxes within −10° to 30° E, 38° to 70° N, are also shown. ACC values in the plot are followed by its standard deviation computed after Goddard et al. (2013). ACCs obtained from detrended time series are indicated in brackets.

European continent. The obtained skill is higher when the five-layer soil scheme is used, reflecting the high skill found particularly in the late period. Indeed, in large parts of central Europe negative ACCs found for the early period appear to cause decreased skill derived from the entire period (Figure S2). Thus, the hindcast skill obtained for the different regions clearly originates from the more recent years and from the higher complexity of the soil scheme.

In the following, we investigate why the hindcast skill increases in MPI-ESM with the new five-layer soil-hydrology scheme. First the direct impact of the more realistic soil scheme on land-atmosphere coupling is investigated; then we evaluate possible improvements in predicting large-scale atmospheric circulation patterns by analyzing the 500 hPa geopotential height surface, which may provide feedbacks for surface temperature predictions.

We start with the examination of the two assimilation experiments which provide the initial conditions for the hindcast sets. In the two experiments from which hindcasts are started soil moisture is assimilated indirectly by nudging divergence, vorticity, temperature, and surface pressure in the atmospheric model component. In order to evaluate the performance of this indirect soil moisture assimilation we compute the correlation between simulated root-zone soil moisture and ERA-Land soil moisture (Balsamo et al., 2015) averaged for each month over southern Europe, the region which was extensively studied in the context of the European heat wave 2003 (e.g., Weisheimer et al., 2011). In spring the indirect soil moisture assimilation performs only fairly realistic when the bucket scheme is used (ACC ≈ 0.75), while the ACC for root-zone soil moisture exceeds 0.85 in April when the five-layer soil-hydrology scheme is used (Figure 2). This ACC increase is at least partly due to the extreme year 2003. While a negative soil moisture anomaly during spring 2003 can be simulated with the five-layer soil-hydrology scheme, the model fails to reproduce this anomaly when the bucket scheme is used (Figure S3). This implies that in the latter setup MPI-ESM is not suited to investigate possible linkages between spring soil moisture and summer near-surface air temperature during the 2003 summer heat wave period.

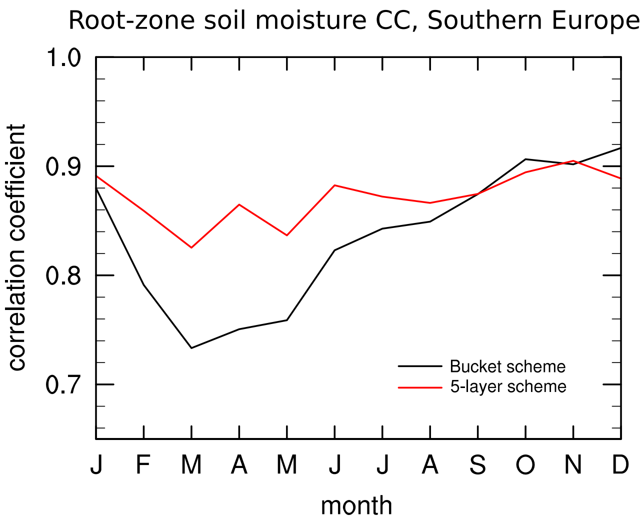

Figure 2. The correlation coefficient for southern European root-zone soil moisture (0° to 25° E, 42° to 52° N) computed over each month within 1981–2010 from the two assimilation runs performed with MPI-ESM differing only in the employed soil configuration. ERA-Land reanalysis data were used as reference data.

In order to evaluate the impact of the soil scheme on soil moisture-atmosphere coupling we investigate the correlation between 2 m temperature and evapotranspiration (transpiration plus bare soil evaporation) as a measure for the soil state. Consistent with previous studies (e.g., Seneviratne et al., 2006) we find that the border between wet and dry soil states separates southern Europe from central and northern Europe (Figures 3a and 3b). While in southern Europe the correlation is negative, implying that evapotranspiration is limited here by the available soil moisture, the positive correlation in central and northern Europe shows that evapotranspiration is limited by the available energy here. This general pattern is found to be independent of the soil scheme used in hindcasts. However, in a few regions, such as Scandinavia and parts of central Europe, hindcasts with different soil schemes show significantly different soil states (Figure 3c). Large parts of these regions match with regions where significant hindcast skill for 2 m summer temperature is obtained only with the five-layer scheme (Figures 1a and 1b).

In order to investigate whether the skill improvement can be linked to improved land-atmosphere coupling obtained with higher complexity of the soil scheme, we further analyze the correlation between 2 m temperature and transpiration, the plants' contribution to evapotranspiration (Figures 3d and 3e). We indeed find differences between the two soil schemes primarily in regions where significant hindcast skill for 2 m temperature is obtained only with the five-layer scheme (Figure 3f). With the bucket scheme more water is available for the plants' transpiration in parts of central Europe and Scandinavia compared to the five-layer scheme. The remaining part of the evapotranspiration, the bare soil evaporation, also significantly varies with the soil configuration of the model (Figures 3g and 3h). While the strength of the positive correlation between 2 m temperature and bare soil evaporation differs in central and northern Europe, the correlation even reverses in southern Europe (Figure 3i). Here the bare soil evaporation is limited by the available water in the soil when the bucket scheme is used, whereas enough water for bare soil evaporation is available when the five-layer scheme is used. This shows that the soil state in a grid cell can differ substantially among the two soil schemes, since the plants can access the entire water supply of a grid cell in the bucket scheme, while the five-layer soil scheme allows for water to exist below the root zone generating soil moisture memory. This different behavior of the two soil schemes in southern Europe may cause the skill improvement particularly in the Balkan region.

Reanalysis data covering Europe from 1981 to 2010 is available only for evapotranspiration; however, the amount of actual measurements that were used to generate the reanalysis is limited. Nevertheless, we find the five-layer scheme to show higher agreement with ERA-Land reanalysis than the bucket scheme, particularly in parts of central Europe and Scandinavia (Figure S4) which match with regions where significant hindcast skill for 2 m temperature is obtained only with the five-layer scheme (Figures 1a and 1b).

The direct improvement of land-atmosphere coupling is one possible source of the hindcast skill improvement of 2 m summer temperatures over Europe obtained with the introduction of the five-layer soil-hydrology scheme. In order to investigate whether an indirect improvement of the large-scale atmospheric circulation may also be a source for the improved 2 m temperature hindcast skill, we analyze the JJA-mean 500 hPa geopotential height surface in the two hindcast sets (Figures 4a and 4b). The definition of large-scale circulation patterns, such as atmospheric blocking regimes, is based on the 500 hPa surface. Our evaluation shows a significant improvement of the predicted anomaly in 500 hPa geopotential height in parts of central Europe and Scandinavia when the five-layer scheme is used (Figure 4c). Also, the atmospheric blocking frequency itself shows improved hindcast skill with the five-layer soil scheme (Figure S5). However, the occurrence frequency and amplitude of blocking events might be too irregular to allow for a robust skill evaluation (Figure S7). In fact, when summers with extreme atmospheric blocking regimes are excluded from the analysis, the obtained hindcast skill for blocking frequency and 500 hPa geopotential height drops substantially in

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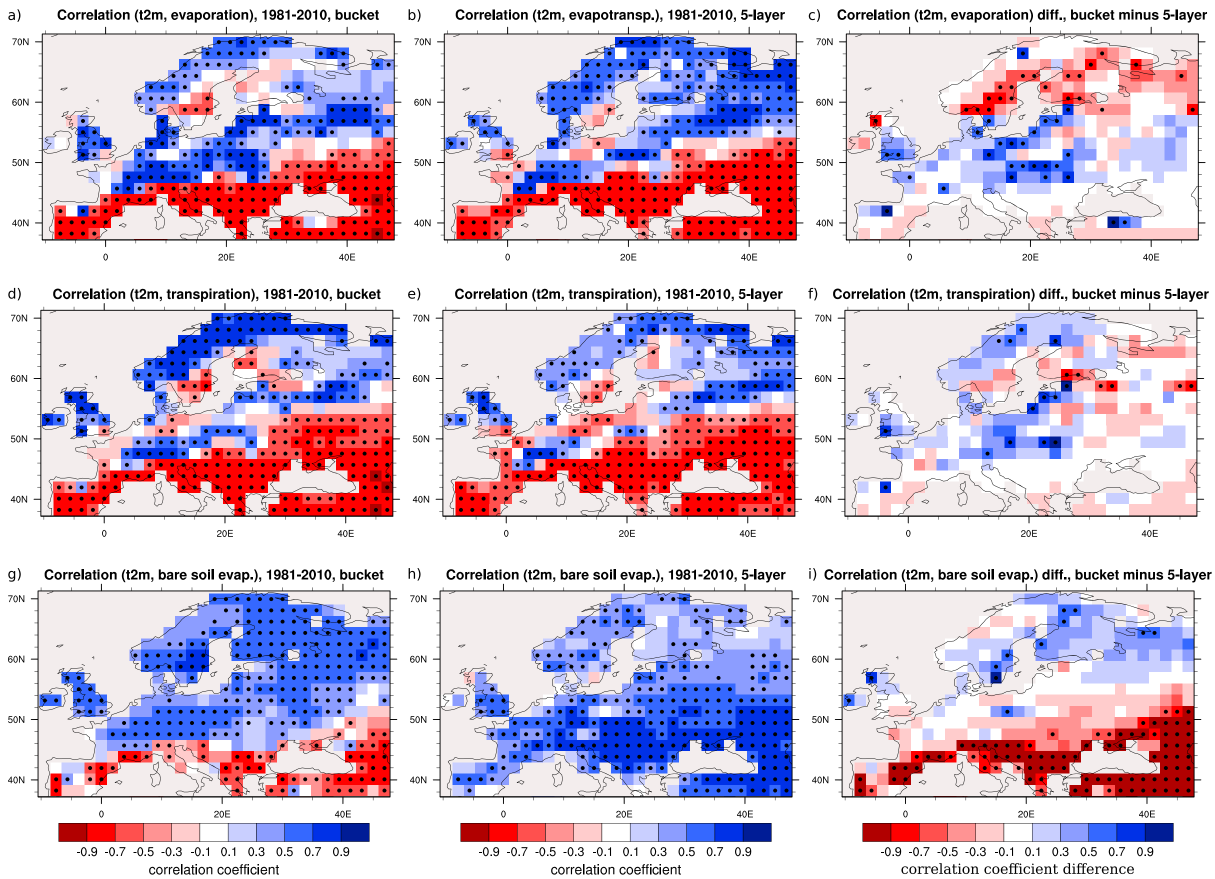

Figure 3. Correlation coefficients between JJA-mean 2 m temperature and evapotranspiration computed from hindcasts using (a) the bucket soil scheme and (b) the five-layer soil scheme. (d, e) The correlation between 2 m temperature and the plants' transpiration and (g,h) the bare soil evaporation are also shown. Differences are depicted in the right column (Figures 3c, 3f, and 3i). Dotted regions indicate significant correlation coefficients at the 95% level obtained from a bootstrap significance test (Goddard et al., 2013).

the respective region (Figures S8 and S9) and further indicates that the improved soil scheme affects extreme years and associated atmospheric circulation.

In summary, we find that with increased complexity of the soil scheme also large-scale atmospheric circulation patterns are predicted more realistically in parts of central Europe and Scandinavia, providing a feedback mechanism that potentially contributes to the improvement found for 2 m temperature predictions.

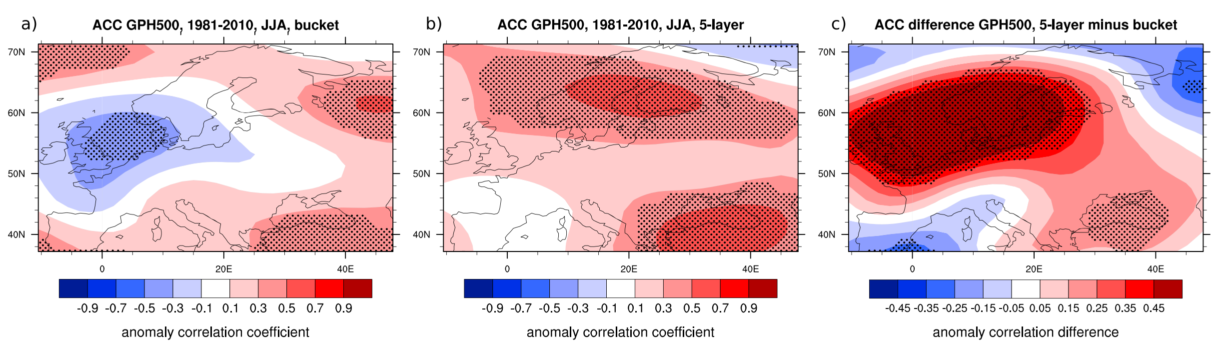

Figure 4. Anomaly correlation coefficients (ACCs) for ensemble mean 500 hPa geopotential height over Europe as computed from hindcasts using (a) the bucket soil scheme and (b) the five-layer soil scheme. ERA-Interim was used as reference data. Dotted regions indicate significant ACCs at the 95% level obtained from a bootstrap significance test (Goddard et al., 2013). (c) The ACC difference is depicted with significance computed after the modified Fisher transformation described by Siegert et al. (2017).

4. Summary and Conclusions

State-of-the-art seasonal prediction systems with different complexities and initialization strategies show only moderate skill for the prediction of European summer temperatures. A recent multimodel study showed, however, that climate models are capable to significantly predict detrended summer temperature anomalies at least in certain European regions over the period 1992–2010 (Ardilouze et al., 2017). Here we use one of the models evaluated within this multimodel study, the MPI-ESM model, with two different soil configurations, a bucket and a five-layer configuration. In this way, we investigate the impact of a more realistic soil model component on the hindcast skill for European 2 m temperatures obtained from 10-member hindcast sets simulated with the two different soil configurations. We find substantial regions with significant hindcast skill over the European continent only with the five-layer soil scheme. The obtained skill originates from the second half (1996–2010) of the entire period of hindcasts (1981–2010) and is primarily due to a better representation of extreme events, which is consistent with the results of Ardilouze et al. (2017). Furthermore, we investigate whether the increase in hindcast skill is caused by the direct improvement of land-atmosphere coupling or by the indirect improvement of the large-scale atmospheric circulation in the model.

The role of soil moisture is crucial for land-atmosphere coupling. In spring, soil moisture anomalies turn out to be more realistically simulated if the five-layer soil scheme is used. Consequently, the behavior of the plants' transpiration differs among the model setups, although the distribution of regions with wet and dry soil states is in both model setups generally comparable to other studies (e.g., Seneviratne et al., 2006). Previous studies showed that the bucket soil scheme tends to overestimate evapotranspiration due to deficiencies in the simulation of the plants' transpiration (Henderson-Sellers et al., 1996). With the new five-layer scheme a part of the soil water is located below the root zone and hence inaccessible for the plants. In parts of central Europe and Scandinavia the behavior of the plants' transpiration differs significantly among the model setups, and the evaluation of land-atmosphere coupling in reanalysis data shows higher agreement here with results obtained with the five-layer scheme compared to the bucket scheme. Thus, we conclude that improved land-atmosphere coupling is one possible source of the improvement in European summer temperature hindcast skill.

Additionally, we also find the hindcast skill of the 500 hPa geopotential height surface over Europe to improve with increased complexity of the soil scheme. This atmospheric region can be considered as the "steering" level of synoptic features (e.g., Carlson, 1991), such as atmospheric blocking regimes (Scherrer et al., 2006). Changing the soil configuration introduces differences in local weather systems which appear to eventually cause more realistic large-scale atmospheric circulation patterns. The improved prediction of the 500 hPa geopotential height surface over Europe is a response to the increased complexity in the soil scheme but also another possible (indirect) source of the skill improvement in predictions of European summer temperatures, since it constitutes a potential feedback mechanism. Our first evaluation of atmospheric blocking events suggests that also the hindcast skill of this specific type of large-scale atmospheric circulation events is improved with the five-layer soil scheme (Figures S5 to S7). When years with extreme blocking frequencies are excluded from the analysis, the obtained hindcast skill drops substantially only in the respective region (Figures S8 and S9), suggesting a certain regional variation of extreme blocking events. Additionally, occurrence frequencies and amplitudes of blocking events are highly irregular (Figure S7), so that a robust evaluation of the predictive skill of these events, either with larger data sets or by implementing new statistical methods, is subject to future studies.

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