Importance of surface roughness for the local biogeophysical effects of deforestation

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Key Points:

- The relevance of surface roughness change on the surface energy balance following deforestation is poorly characterized globally.
- A climate model simulation reveals that surface roughness dominates the local surface temperature change signal in most geographic regions.
- Model outcomes are consistent with observed changes in surface temperature across annual, diurnal, and seasonal time scales.

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Abstract

Deforestation influences surface properties such as surface roughness, resulting in changes in the surface energy balance and surface temperature. Recent studies suggest that the biogeophysical effects are dominated by changing roughness, and it remains unclear whether this can be reconciled with earlier modeling studies that highlighted the importance of a reduction of evapotranspiration in the low latitudes and a reduction of net shortwave radiation at the surface in the high latitudes. Here, we analyze the local effects of deforestation on surface energy balance and temperature in the MPI-ESM climate model by performing three separate experiments: switching from forest to grass *all* surface properties, only surface albedo, and only surface roughness. We find that the locally induced changes in surface temperature are dominated by changes in surface roughness for the annual mean, the response of the diurnal amplitude as well as the seasonal response to deforestation. For these three quantities, the results of the MPI-ESM lie within the range of observation-based data-sets. Deforestation-induced decreases in surface roughness contribute substantially to winter cooling in the boreal regions and to decreases in evapotranspiration in the tropics. By comparing the energy balance decompositions from the three experiments, the view that roughness changes dominate the biogeophysical consequences of deforestation can be reconciled with the earlier studies highlighting the relevance of evapotranspiration.

1 Introduction

Deforestation not only releases large amounts of carbon into the atmosphere (Le Quéré et al., 2018), but also influences the surface properties such as surface albedo, surface roughness, and evapotranspirative efficiency (E. L. Davin & de Noblet-Ducoudre, 2010). Changes in these surface properties alter the exchange of heat, moisture, and momentum between the surface and the atmosphere. It is important to understand the mechanisms by which the changes in the surface properties influence climate, because forest management practices (Anderson et al., 2010) or geoengineering strategies (E. Davin, Seneviratne, Ciais, Olioso, & Wang, 2014; Seneviratne et al., 2018; Thiery et al., 2017) may be designed to alter single surface properties in order to influence climate, in particular surface temperature.

When analyzing the mechanisms underlying deforestation, one must differentiate between surface properties and components of the surface energy balance (Fig. 1). Locally, deforestation leads to a change in surface properties, e.g. surface albedo may increase when forest is replaced by brighter grassland. The changes in surface properties then translate into changes in the surface energy balance (e.g., less net shortwave radiation absorbed by the surface, but also changing the latent and sensible heat fluxes) and finally changes in surface temperature at the location of deforestation (Fig. 1). The changes in components of the surface energy balance and surface temperature that are triggered locally at a location of deforestation are henceforth referred to as the 'local effects'. Furthermore, changes in the physical state of the surface may affect the atmospheric conditions such as clouds (e.g., Teuling et al., 2017) but also atmospheric temperature and humidity (e.g., E. L. Davin & de Noblet-Ducoudre, 2010). Through changes in heat and moisture advection, the changes in the atmosphere may not only be seen at the location of deforestation but also at locations that were not deforested, thus resulting in changes in the surface energy balance at these locations. These remote changes are henceforth referred to as 'nonlocal effects'. While the nonlocal effects may dominate the global mean response of surface temperature (Winckler, Reick, Lejeune, & Pongratz, 2018), this study focuses on the *local* biogeophysical effects for three reasons: 1) In contrast to the nonlocal effects, the local effects on surface temperature are largely independent of the spatial extent and location of deforestation (Winckler, Reick, Lejeune, & Pongratz, 2018). Thus, the focus on the local effects enables process understanding that is independent of (to some extent arbitrary) choices of deforestation scenarios such as historical deforestation, possible future de/afforestation or idealized large-scale de/afforestation that alter not only local but also large-scale conditions like the background climate. 2) The local effects on surface temperature are relevant for forest- and other land-based strategies that aim at locally adapting to a warming climate. 3) The local effects in the climate model are relevant for the comparison with, and the interpretation of, observation-based data-sets because these by construction exclude any nonlocal effects (Alkama & Cescatti, 2016; Bright et al., 2017; Duveiller, Hooker, & Cescatti, 2018a; Li et al., 2015).

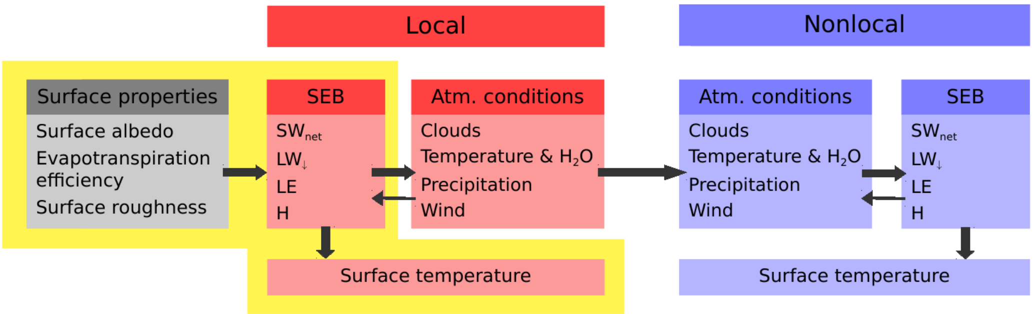

Figure 1. Illustration of how surface temperature is influenced by deforestation. At the location of deforestation, changes in surface properties translate into changes in the surface energy balance (SEB), and these result in changes in the surface temperature ('local effects'). The changes in the local surface energy balance can trigger changes in the atmospheric conditions, and these can also propagate to locations without deforestation, influencing the surface energy balance and the surface temperature there ('nonlocal effects'). The focus of this study (indicated by yellow) is the relation between changes in surface properties and resulting local effects on the surface energy balance and the surface temperature.

In order to understand the mechanisms that are responsible for deforestation-induced changes in surface temperature, previous studies mostly focused on changes in the components of the surface energy balance. A satellite-based study showed that the local effects of deforestation in high latitudes lead to a surface cooling due to a reduction in net shortwave radiation at the surface, although some of this cooling is balanced by a reduced loss of sensible heat from the surface to the atmosphere (Duveiller, Hooker, & Cescatti, 2018b). Furthermore, the local effects of deforestation in lower latitudes lead to a surface warming due to a reduction in evapotranspiration (and hence latent heat flux) (Duveiller et al., 2018b). These findings are in agreement with climate modeling studies on idealized global-scale deforestation (e.g., Bala et al., 2007; Bathiany, Claussen, Brovkin, Raddatz, & Gayler, 2010; Claussen, Brovkin, & Ganopolski, 2001; Devaraju, Quesada, Bala, & de Noblet-Ducoudré, 2018), which argued that the boreal cooling is caused by a decrease in shortwave radiation and the tropical warming is caused by a decrease in evapotranspiration. Some observational and climate modeling studies also quantified how changes in the different terms of the surface energy balance contributed to changes in surface temperature by an explicit decomposition the surface energy balance (Methods) for deforestation (e.g., Boisier et al., 2012; Vanden Broucke et al., 2015; Winckler, Reick, & Pongratz, 2017a). While these studies provide valuable information about deforestation-induced changes in the surface energy balance, neither the observation-based nor the model-based studies investigated which surface property is responsible for the analyzed changes.

Some climate model studies addressed this question of attribution of changes in surface temperature to changes in particular surface properties (surface albedo, surface roughness, evapotranspirative efficiency; changes in evapotranspirative efficiency may be caused by changes in a wide set of parameters in a climate model, e.g. changes in leaf area index and canopy conductance). For this attribution, simulations were performed in which only one surface property at a time was switched from forest to grass values (Bell, Tompkins, Bouka-Biona, & Seidou Sanda, 2015; E. L. Davin & de Noblet-Ducoudre, 2010). For global-scale deforestation, the study by E. L. Davin and de Noblet-Ducoudre (2010) found that changes in surface albedo (leading to strong global cooling) dominate changes in evapotranspirative efficiency and surface roughness (leading to warming). However, due to the large scales at which the surface properties in these studies are changed, the changes in surface temperature in their studies may be dependent on the presence of strong nonlocal effects, which are the main pathway for the albedo-induced change in surface temperature (Winckler, Reick, Lejeune, & Pongratz, 2018). Thus, it still remains unknown which surface property was responsible for the changes in surface temperature due to deforestation with regards to the local effects. For an improved understanding on how deforestation leads to changes in biophysical conditions, it would be desirable to link more directly the studies focusing on the surface energy balance, e.g. by a surface energy balance decomposition, and the studies altering individual surface properties – the latter studies focused predominantly on changes in surface temperature, with little quantitative information on changes in the terms of the surface energy balance. It seems intuitive to interpret high-latitude cooling associated with reduced shortwave absorption as attributable to albedo changes, or tropical warming associated with reduced evapotranspiration as attributable to changes in evapotranspirative efficiency, but this attribution of changes in surface energy balance components to changes in surface properties is not unique, and as we will show, changes in surface roughness also play an important role here.

Another way to attribute the deforestation-induced changes in surface temperature to physical mechanisms was developed by Juang, Katul, Siqueira, Stoy, and Novick (2007). They derived analytical expressions to attribute the surface temperature response (mainly due to local effects) to changes to specific "eco-physiological" or "intrinsic biophysical mechanisms" (IBPM). Such expressions have recently been applied to analyze climate model output (Burakowski et al., 2018; Chen & Dirmeyer, 2016; Devaraju et al., 2018; Rigden & Li, 2017) or in-situ observations (Bright et al., 2017; Juang et al., 2007; Lee et al., 2011). Changes in surface temperature were attributed to a 'surface albedo' term and an 'energy redistribution' term (Lee et al., 2011) which is often divided in an 'aerodynamic resistance term' (or 'roughness term') and a 'bowen ratio term' (Lee et al., 2011). These studies found that the roughness term dominates the locally induced changes in surface temperature. However, it is unclear how these terms (e.g. 'roughness term') relate to the surface properties (e.g. 'surface roughness') that were investigated in the climate models.

The importance of the 'roughness term' in the IBPM studies seems to suggest that surface roughness is important for the locally induced changes in surface temperature. The importance of the 'roughness term', both for deforestation-induced high-latitude cooling and low-latitude warming, seems to contradict the studies that focus on changes in the surface energy balance components, which highlight the importance of a reduction of shortwave radiation for the high-latitude cooling and a reduction of latent heat (evapotranspiration) for low-latitude cooling. It remains unclear whether these findings are indeed contradictory, or whether the apparent discrepancies can be explained by the presence of nonlocal effects (mainly excluded in the IBPM method, included in most climate modeling studies) or by a different focus of the studies (changes in surface properties vs. changes in surface energy fluxes).

To close this gap, we investigate the role of surface roughness for the local effects of deforestation on the surface energy balance and surface temperature. Using simulations performed with the climate model MPI-ESM, we contrast the local effects of concurrently changing all surface properties that are affected by deforestation (surface albedo, surface roughness, evapotranspirative efficiency) with the local effects of only changing surface roughness and only changing surface albedo. By changing only surface roughness, we are able to isolate the aerodynamic controls on the surface energy balance from the purely physiological controls (e.g., leaf stomatal control on transpiration), which we then compare to the surface albedo change. The presented analysis relies on a single climate model. In order to check whether the model yields reasonable results, we compare the MPI-ESM results against observation-based data-sets for changes surface temperature at diurnal, seasonal and annual time scales.

2 Methods

2.1 MPI-ESM simulation set-up

Using the climate model MPI-ESM (Giorgetta et al., 2013), several simulations are performed using a horizontal atmospheric resolution of about 1.9° with atmospheric CO_2 concentrations prescribed at a pre-industrial level. After a spin-up of 150 years, 200 years are analyzed. The analyzed variables are free of substantial trends during this period (not shown). In a first simulation ('forest world'), forest plant functional types are prescribed on all vegetated areas (reconstructed from observation-based potential vegetation (Pongratz, Reick, Raddatz, & Claussen, 2008; Ramankutty & Foley, 1999)). Thus, in this simulation forests are prescribed also on present-day grasslands, but not in deserts (Fig. S1). In subsequent simulations, surface properties are switched from forest to grass values in three out of four grid boxes which we call 'change boxes' (Fig. S1). These are distributed according to a regular chessboard-like pattern. This strategy allows us to separate local and nonlocal effects, see section 2.2. Specifically, in one simulation ('deforestation') all surface properties are switched from forest to grass values in the change boxes, while in two other simulations, only surface albedo ('albedo') or surface roughness ('roughness') are switched from forest to grass values in the change boxes. The difference between the forest world and one of the other simulations represents the total (local plus nonlocal) biogeophysical effect of switching the respective surface properties.

The choice of deforesting 3 of 4 grid boxes (instead of e.g. deforesting 1 of 4 grid boxes) is to some extent arbitrary. However, for the local effects, which are the focus of this study, the local effects –both on surface temperature and on the components of the surface energy balance– are largely independent of the number of deforested grid boxes (see Figs. 4*a* and *b* in Winckler et al., 2017a).

2.2 Isolation of the simulated local effects

The total effects are decomposed into the local and nonlocal effects as follows: in the change boxes, we assume that the total effects are the sum of local and nonlocal effects. In contrast, on nearby no-change boxes, only the nonlocal effects occur. In the change boxes, the nonlocal effects can be obtained by horizontal bilinear interpolation of results from neighboring no-change boxes. Then, the local effects in the change boxes can be calculated as the difference between total and nonlocal effects. Thus, the local effects are the climate signal in the change boxes that goes beyond the signal in surrounding no-change boxes. A detailed explanation of the method is provided in a previous study (Winckler et al., 2017a). This separation of local and nonlocal effects is applied both to changes in surface temperature and to each component of the surface energy balance.

2.3 Comparison of MPI-ESM results to observation-based data-sets

To assess whether the locally induced changes in surface temperature in the MPI-ESM are plausible, they are compared to various observation-based data-sets on the biogeophysical effects of deforestation on surface temperature. These observation-based data-sets contain the temperature change upon 'potential deforestation' (Li et al., 2016), i.e. the changes in radiometric surface temperature that would be caused by a conversion from 100% forests to 0% forests at a given location. The observation-based data-sets represent by design only the local effects (Alkama & Cescatti, 2016; Bright et al., 2017; Duveiller et al., 2018b; Li et al., 2015), e.g. because they compare temperatures (Alkama & Cescatti, 2016) or temperature changes (Li et al., 2015) in neighboring locations; Nonlocal effects would be seen in neighboring locations with and without forest cover change and are thus by construction not contained in these data-sets. We focus on zonally averaged changes in annual mean surface temperature, the magnitude of the diurnal cycle, and the seasonal cycle. We consider changes in radiometric surface temperature from three satellite-based data-sets (Alkama & Cescatti, 2016; Duveiller et al., 2018a; Li et al., 2015), which are biased towards cloud-free conditions, and one semi-empirical approach based on Fluxnet observations (Bright et al., 2017). The latter is not restricted to cloud-free conditions but does not contain information about changes in the diurnal amplitude because this data-set is not available for daytime and nighttime separately.

The comparison between the MPI-ESM results and these observation-based data-sets is challenging. First, the background climate differs across the data-sets. While the simulations in the MPI-ESM are subject to a modeled background climate under pre-industrial CO_2 concentrations, the observation-based data-sets focus on the more recent past (years 2001-2011 in Bright et al. (2017), 2002-2013 in Li et al. (2015), 2003-2012 in Alkama and Cescatti (2016), 2000-2015 in Duveiller et al. (2018b)). The difference in background climate could influence the results for the total (local plus nonlocal) biogeophysical effects (Pitman et al., 2011), but also for the locally induced changes in surface temperature (Winckler, Reick, & Pongratz, 2017b) that are analyzed here. However, background climate between pre-industrial and present day did not change strongly enough to substantially change the biogeophysical deforestation effects (e.g., Fig. 5 in de Noblet-Ducoudré et al., 2012). Second, the spatial availability of the observation-based data-sets differ, see Fig. S2. For the zonal averages shown below, values for the MPI-ESM are only considered where at least one of the observation-based data-sets is available. Third, it is challenging to compare the surface temperature in the MPI-ESM with the radiometric surface temperature from the observation-based data-sets (Jin & Dickinson, 2010; Winckler, Reick, Luyssaert, et al., 2018). These inconsistencies complicate a fully consistent comparison between the MPI-ESM results and the observation-based data-sets. However, the observation-based data-sets can still be used to check whether the model results are plausible by assessing whether there is a qualitative match in the response of the annual means, the diurnal amplitude and seasonal response to deforestation.

2.4 Energy balance decomposition for the changes in surface temperature due to deforestation

Changes in surface temperature result from the changes in the components of the energy balance (Fig. 1). Changes in net shortwave radiation, incoming longwave radiation, sensible heat flux, and latent heat flux are balanced by changes in emitted longwave radiation, which is directly related to surface temperature (T_{surf}) via the Stefan-Boltzmann law. Thus, a change in any of the components of the surface energy balance (in units W/m^2) can be expressed as a change in surface temperature (in units K) that would be triggered if only this particular flux was changed and all other surface energy balance components were held constant:

$$\Delta T_{\text{surf}} = \frac{1}{4\sigma\epsilon T_{\text{surf}}^3}(\Delta\text{net shortwave} + \Delta\text{incoming longwave} - \Delta\text{latent} - \Delta\text{sensible}), \quad (1)$$

where σ is the Stefan-Boltzmann constant and ϵ is emissivity and is set to 1. Changes in ground heat flux are not considered because we assume that deforestation-induced changes in ground heat flux are negligible on the time scales that we consider in this study. More details on the energy balance decomposition approach can be found elsewhere (e.g., Boisier et al., 2012; Luyssaert et al., 2014).

In the following, we first separate local and nonlocal effects for each existing simulation ('all','only roughness', 'only albedo'). For each simulation, this separation is performed both for surface temperature and for every component of the surface energy balance (net shortwave radiation, incoming longwave radiation, sensible heat flux, and latent heat flux). Using equation (1), the respective changes are then converted into temperature units.

3 Results

3.1 Simulated local effects on surface temperature are largely consistent with observations

We compare zonally averaged values from the MPI-ESM simulations with observation-based data. In these simulations, deforestation triggers an annual mean local cooling north of 50°N and a warming further south (Fig. 2 *a*), and the surface temperature changes in the MPI-ESM lie within the range of observation-based data-sets (see also Winckler, Reick, Lejeune, and Pongratz (2018)). The model response is at the lower end of the satellite-based data-sets and closer to the Fluxnet-based estimate (Bright et al., 2017), which is free of the cloud bias that is inherent in the satellite-based estimates (Alkama & Cescatti, 2016; Duveiller et al., 2018a; Li et al., 2015). The diurnal cycle of surface temperature is amplified by the local effects of deforestation, both in the model and the satellite-based estimates (Fig. 2b). In the low latitudes, the diurnal cycle over grasslands is up to 4 K larger than over forests. Only north of 50°N does the MPI-ESM overestimate the amplification of the diurnal cycle. Concerning the seasonal response to deforestation, the model and the observation-based estimates largely agree (Fig. 2c and d). Both in northern-hemispheric winter and summer, the locally induced changes in surface temperature in the MPI-ESM closely follow the Fluxnet-based estimate (Bright et al., 2017) and lie at the lower end of the satellite-based estimates (Alkama & Cescatti, 2016; Duveiller et al., 2018a; Li et al., 2015). Only the observations' winter warming north of 65°N is not captured by the model.

To summarize, the local effects on changes in zonal mean surface temperature in the MPI-ESM are largely in line with the observation-based estimates, both for the annual mean, diurnal, and seasonal response to deforestation. Spatial patterns also align well with observations (Figs S2-S5). Our results for surface temperature in the MPI-ESM are also in good qualitative agreement with a study that more comprehensively evaluated the sensitivity of the CLM4.5 model to land cover (Meier et al., 2018). Although it cannot be excluded that the MPI-ESM is right for the wrong reasons, the broad agreement with the observations makes it seem plausible that the MPI-ESM correctly represents the most relevant mechanisms that are responsible for changes in surface temperature that are locally induced by deforestation. This could be evaluated in more detail in future studies.

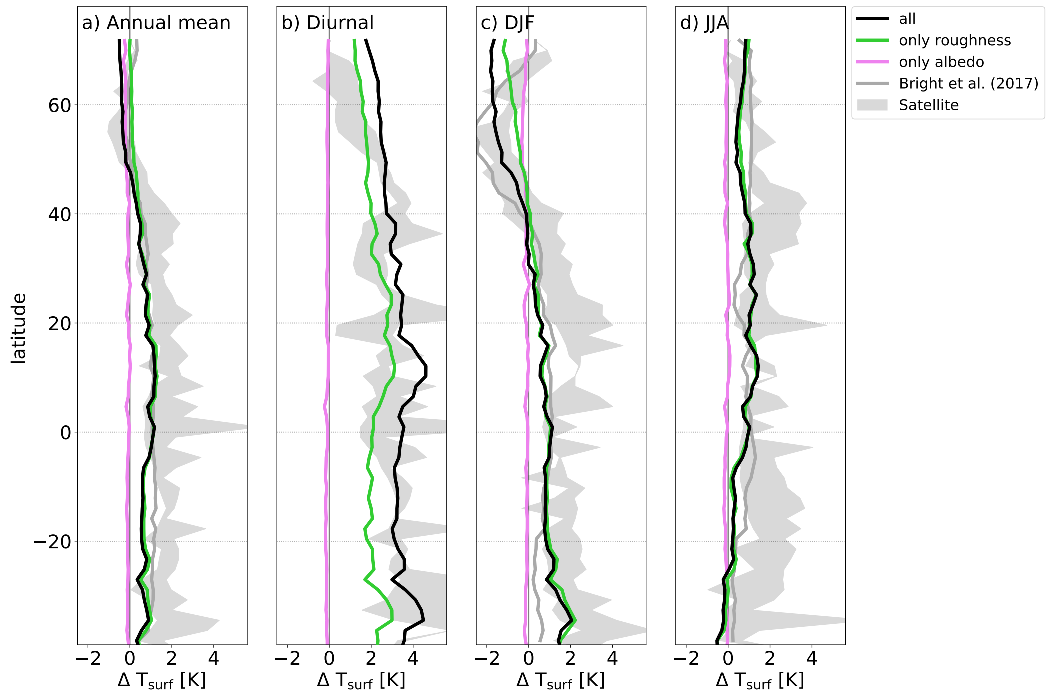

Figure 2. Comparison of the MPI-ESM to observation-based data-sets. Deforestation-induced local effects on surface temperature for a) the annual mean temperature, b) the amplitude of the diurnal cycle, c) changes in December to February temperature, d) changes in June to August temperature. Locally induced changes in surface temperature for (black) changing all surface properties from forest to grass values in the MPI-ESM, and contributions of changing only surface roughness or only surface albedo from tree to grass values. Observation-based data-sets from (grey line) Fluxnet (Bright et al., 2017) and (grey shading) remote sensing from satellites (Alkama & Cescatti, 2016; Duveiller et al., 2018a; Li et al., 2015). The data-set by Bright et al. (2017) does not contain diurnal values. The values for the MPI-ESM are zonally averaged where at least one of the observation-based data-sets is available. The respective maps are shown in Figs. S2-S5.

3.2 Simulated local effects are to a large extent caused by changes in surface roughness

3.2.1 Annual mean

The annual mean changes in surface temperature due to the local effects of deforestation can predominantly be explained by changes in surface roughness in most latitudes (Fig. 2 a). In contrast, changes in surface albedo locally trigger only small changes in annual mean surface temperature.

Every surface property influences every surface energy balance component (Fig. 1). Here, we provide an energy balance decomposition (Methods) for the changes in surface temperature that are triggered by changing all surface properties affected by deforestation, changing only surface roughness, and changing only surface albedo (Fig. 3). Changes in surface roughness turn out to be the major driver of the local responses of latent and sensible heat fluxes to deforestation (Fig. 3 a and b). If all other surface energy balance components were fixed, a reduction of surface roughness would result in less evapotranspiration (less release of latent heat into the atmosphere) over grass compared to forests.

This reduction would result in a strong warming (up to 3 K in the inner tropics), but this warming is partly balanced by the increased sensible heat flux, such that changes in surface roughness in the inner tropics locally trigger a warming of around 1 K (Fig. 3 a and b). Changes in surface albedo locally trigger a decrease in net shortwave radiation. This decrease, if all surface energy balance components were kept fixed, would lead to a surface cooling of around 2 K across most latitudes. However, this cooling from decreased net shortwave radiation is largely balanced by the decreased latent and sensible heat fluxes, such that surface temperature barely responds (Fig. 3 c). Note that while the change in surface roughness is important for the local effects shown here, the change in surface albedo dominates the nonlocal effects in these simulations (Fig. S7).

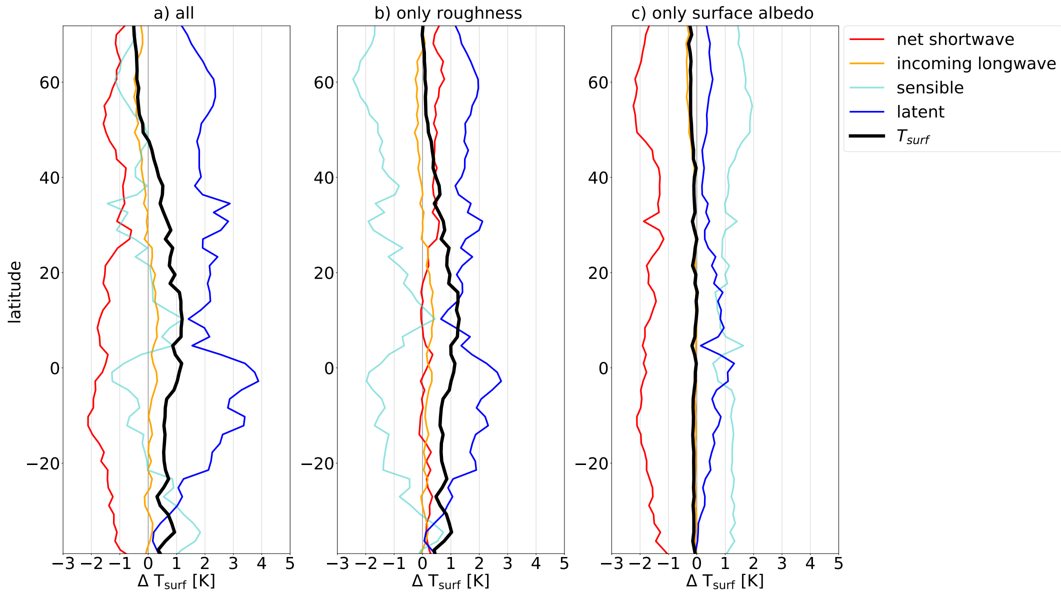

Figure 3. Energy balance decomposition of the locally induced changes of annual mean surface temperature in the MPI-ESM. The lines denote deforestation-induced changes in surface energy balance components for simulations changing (a) all surface properties, (b) only surface roughness, and (c) only surface albedo. Shown is their locally induced impact on surface temperature (same lines as in Fig. 2*a*), net shortwave radiation, incoming longwave radiation, sensible heat, and latent heat, zonally averaged over areas where at least one of the observation-based data-sets is available. Note that warming from latent heat is caused by a reduction in evapotranspiration.

3.2.2 Diurnal cycle

Changes in surface roughness are responsible for around two thirds of the amplification of the diurnal cycle in the MPI-ESM throughout the latitudes (Fig. 2 b). Changes in albedo are negligible for local effects on the diurnal cycle of surface temperature. Approximately one third of the amplification of the diurnal cycle is neither explained by the change in surface roughness nor the change in surface albedo. This residual has to be caused either by changes in evapotranspirative efficiency or by interactions between the three surface properties. Possible mechanisms for the roughness-induced changes in the diurnal amplitude are provided in the discussions section.

3.2.3 Seasonal cycle

Changes in surface roughness are responsible for most of the deforestation-induced warming in the tropics and in the summer months of the respective hemisphere (Fig. 2 c and d). While some of the boreal winter cooling is caused by changes in the surface albedo, a substantial fraction of the cooling in DJF are caused by changes in surface roughness in the MPI-ESM (Fig. 2 c).

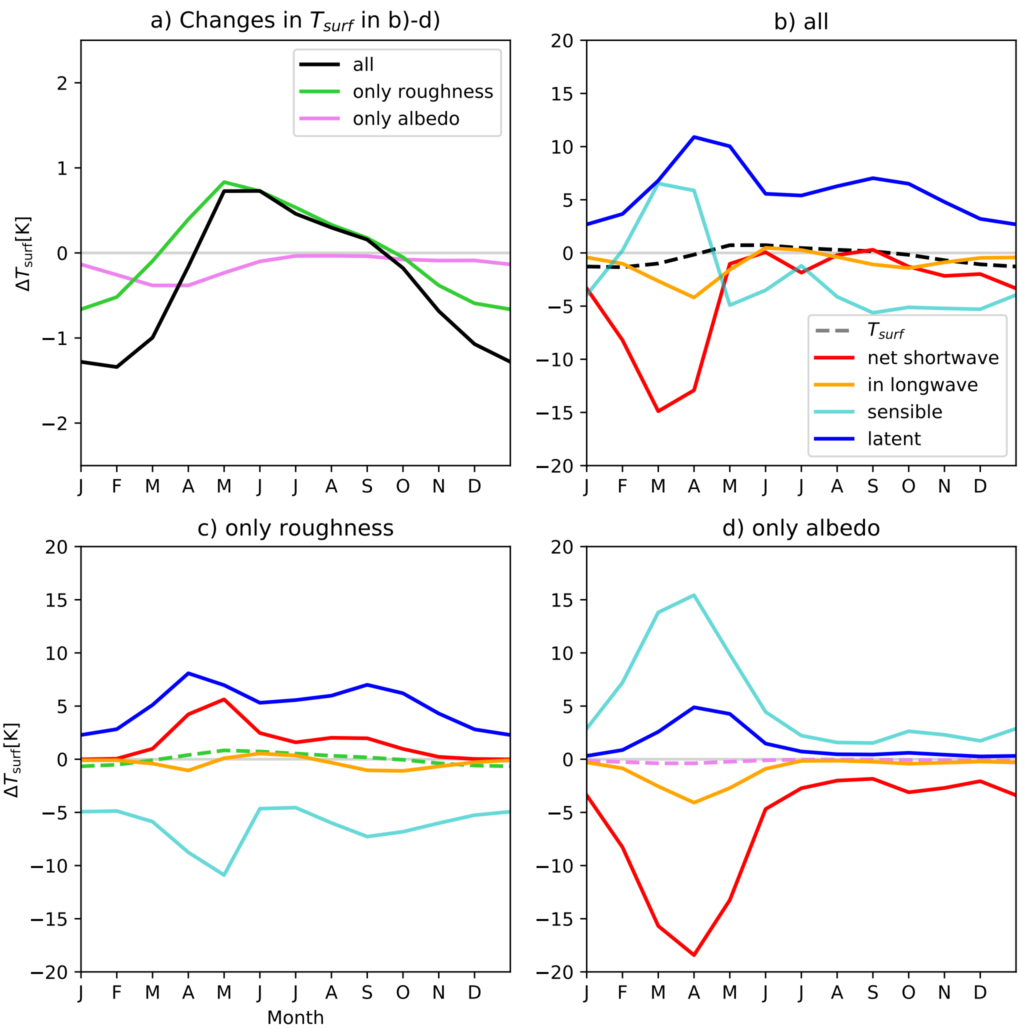

Figure 4. Seasonality in areas with boreal spring snow cover. a) Changes in the monthly mean surface temperature [K] due to the local effects of changes in all surface properties, only surface roughness, and only surface albedo. The solid lines in a) are the dashed lines in b)- d), where the energy balance is decomposed for the local effects on changes in *b*) all surface properties, *c*) only surface roughness, and *d*) only surface albedo. The values of the energy balance components were converted from W/m^2 into Kelvin as described e.g. in the study by Luyssaert et al. (2014). Values are averaged over mid- and high latitude land areas with spring snow cover (snow cover fraction exceeds 0.5 in March, Fig. S6). Note that the values on the y-axis differ between the plots.

To further investigate the surprisingly minor importance of surface albedo compared to surface roughness, we consider the deforestation-induced boreal winter cooling and focus on areas where the influence of surface albedo is expected to be the strongest, namely areas with snow cover in spring (Bonan, 2008) (here snow cover in March). From the surface property perspective, even in these areas (see Fig. S6) the changes in surface roughness are more important for the local cooling in winter (DJF) than the changes in surface albedo (Fig. 4 a). From the energy balance perspective, the roughness-induced local DJF surface cooling arises from changes in the sensible heat flux (Fig. 4 *c*). However, the sensible heat flux appears not to be the dominant driver of the winter cooling when considering changes in all surface properties (Fig. 4 *b*) because of concurrent changes in other surface properties. For instance, the cooling from the albedo-induced reduction in net shortwave radiation (especially in April and May, (Fig. 4 *d*)) is balanced by a warming from sensible heat flux. This illustrates that the combination of changes in surface properties influences the surface energy balance in a complex way so that an energy balance decomposition as shown in Fig. 4*b* is not sufficient to infer the responsible surface properties for a change. Instead, it factorial experiments are needed to disentangle concurrent changes in the surface energy balance that are caused by changes in the different surface properties.

4 Discussion and conclusions

Our findings show that in the MPI-ESM, changes in surface roughness largely control the local effects of deforestation. Changes in surface roughness in the MPI-ESM dominate the annual and seasonal mean local responses by surface temperature to local deforestation (Fig. 2 *a*, *c* and *d*). This seems to contradict previous studies on the biogeophysical temperature effects of global-scale deforestation in climate models: previous studies found that a reduction of net shortwave radiation at the surface dominates the boreal cooling and a reduction in evapotranspiration dominates the tropical warming (e.g., Bala et al., 2007; Bathiany et al., 2010; Claussen et al., 2001; Devaraju et al., 2018). This apparent discrepancy between our and their results may result from two major differences between the studies: First, our study considers the changes in surface properties (e.g., surface roughness) while the previous studies (with exceptions of (Bell et al., 2015; E. L. Davin & de Noblet-Ducoudre, 2010)) did not separate the influences of the different surface properties but based their conclusions either on mere plausibility arguments, or, if more elaborated, on the deforestation-induced changes in the components of the surface energy balance (e.g., net shortwave radiation or latent heat). If the latter is done, surface albedo is intuitively assigned a large relevance because it is the surface property that is associated with the large reduction in net shortwave radiation. However, it may easily be overlooked that this reduction in shortwave radiation can be largely compensated by reductions in the turbulent heat fluxes, such that the overall influence of changes in surface albedo on the local effects on surface temperature is small. Second, the large-scale changes that were imposed in the previous studies may result in substantial nonlocal deforestation effects. The nonlocal effects, which strongly depend on the areal extent and spatial distribution of deforestation, are mingled with the local effects in these simulation and complicate an understanding of the effects of deforestation at a given location. For instance, changes in surface albedo were found to dominate the boreal cooling (E. L. Davin & de Noblet-Ducoudre, 2010) and both the surface roughness and evapotranspirative efficiency were found to contribute approximately equally to the tropical warming (Bell et al., 2015; E. L. Davin & de Noblet-Ducoudre, 2010). However, changes in surface albedo may mainly affect surface temperature via the nonlocal effects (Winckler, Reick, Lejeune, & Pongratz, 2018), and further changes in evapotranspirative efficiency could trigger changes in cloudiness and precipitation (Ban-Weiss, Bala, Cao, Pongratz, & Caldeira, 2011), which could affect also locations without deforestation. For the particular areal extent and spatial distribution of the simulations used in this study, the nonlocal effects on surface temperature and the surface energy balance decomposition thereof is given in Fig. S7. The present study focuses on the local effects, which may be a reason for the different conclusions concerning the dominant importance of changes in surface roughness between this and previous climate model studies.

In contrast to the climate model studies, satellite-based studies (Alkama & Cescatti, 2016; Duveiller et al., 2018b; Li et al., 2015) only include changes in surface temperature from local effects, so their results could conceptually be compared to our local effects. The satellite-based studies adopted the argumentation from the climate model studies (e.g., Bala et al., 2007; Bathiany et al., 2010; Claussen et al., 2001; Devaraju et al., 2018) that a reduction of net shortwave radiation at the surface dominates the boreal cooling and a reduction in evapotranspiration dominates the tropical warming. It was argued that in boreal regions, the surface cooling is correlated to snow frequency (Li et al., 2015) and thus surface albedo. However, our findings hint to a possible correlation without causation: we find that the local effects of changes in surface roughness cool the surface in the high northern latitudes during winter (Fig. 4), i.e. exactly in cases with a potentially high snow frequency. Our results suggest that surface roughness could dominate this deforestation-induced local cooling. During high-latitude winter, the surface is generally cooler than the atmosphere aloft. Thus, the responsible mechanism for the roughness-induced northern winter cooling could be similar to the hypothesis that was given for the night-time cooling following deforestation (Lee et al., 2011; Vanden Broucke et al., 2015) and corresponding empirical evidence (Schultz, Lawrence, & Lee, 2017). These studies argued that the high surface roughness of forests allows the surface to dissipate energy into the atmosphere during daytime conditions, while during nighttime the high surface roughness of forests allow the surface to gain energy from the warmer atmosphere aloft (Schultz et al., 2017; Vanden Broucke et al., 2015). Accordingly, deforestation, which reduces roughness, reduces daytime surface cooling and nighttime surface warming, leading to a cooler surface at nighs or –in analogy– in winter.

While we separated the effects of changing only surface albedo and only surface roughness, we did not separate the effects of only changing evapotranspirative efficiency. A clean isolation of changes in evapotranspirative efficiency is technically challenging because this surface property is a complex composition of various land surface characteristics, e.g., rooting depth, canopy water holding capacity, photosynthesis, and stomatal conductance (E. L. Davin & de Noblet-Ducoudre, 2010), and some of these variables are not simple parameters but calculated dynamically during a model run. In the way this issue was solved in previous studies (Bell et al., 2015; E. L. Davin & de Noblet-Ducoudre, 2010), possible interactions between the three surface properties are contained in the evapotranspirative efficiency term (although these studies argue that for the total (local plus nonlocal) effects on surface temperature the interactions may be small (Bell et al., 2015; E. L. Davin & de Noblet-Ducoudre, 2010)).

As demonstrated here, the interpretation of the mechanisms underlying the local effects of deforestation depends crucially on the perspective. Concerning deforestation in the low latitudes, from the surface energy flux perspective, the local warming seems to be dominated by the reduction of evapotranspiration. From the surface properties perspective, the changes in surface temperature and evapotranspiration are dominated by changes in surface roughness. Concerning deforestation in the high latitudes, from the surface energy balance perspective, the local cooling seems to be dominated by the reduction in surface net shortwave radiation. However, this does not imply that surface albedo is the surface property that is responsible for most of the overall cooling – we showed that the reduction in net shortwave radiation is locally compensated in its temperature effect by a reduction in losses of latent and sensible heat. Instead, even in areas with high spring snow cover where the influence of surface albedo would be expected to be strong, the local cooling can to a large part be explained by the reduction in surface roughness. Thus, this study reconciles two different views on the mechanisms underlying the local effects of deforestation.

Acknowledgments

Our simulations were performed at the German Climate Computing Center (DKRZ). This work was supported by the German Research Foundations Emmy Noether Program (PO 1751). We want to thank all groups who provided observation-based data. Primary data and scripts used in the analysis and other supporting information that may be useful in reproducing the authors work are archived by the Max Planck Institute for Meteorology and can be obtained by contacting publications@mpimet.mpg.de.

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