Answers to the reviewer comments on the manuscript "Different response of surface temperature and air temperature to the biogeophysical effects of deforestation in climate models" in Earth System Dynamics Discussions

The following pages contain point-by-point responses to the reviewer comments, separately for each of the four reviewers. The last pages contain a latexdiff pdf of the manuscript, indicating where text was removed (red) or added (blue). We found most of the reviewer comments constructive and thus used them to improve the manuscript accordingly. We hope that our adjustments improved the text.

List of most relevant changes in the manuscript:

- Following the reviewer suggestions, we reorganized the text to improve the flow of the Introduction/Discussions and conclusions sections.
- In the maps in the main text, stippling now indicates statistical significance.
- The English was improved in order to facilitate readability.
- Some information was added in the supplementary material, for instance a map illustrating where deforestation was applied in the MPI-ESM model.
- In the results section we extended the discussion on the mechanisms that may contribute to the simulated change in sign for surface and air temperature in the MPI-ESM model.

Response to reviewer 1 of the paper entitled
"Different response of surface temperature and air temperature to deforestation in climate models"
Ref.: esd-2018-66

We would thank the reviewer for the time he/she devoted on reviewing the manuscript, and for his/her helpful comments.

Below are the reviewers comments (***bold italic font***) and our responses to each point (normal font). All line numbers that we provide in our responses refer to the revised version of the manuscript in which track changes are not shown.
The original manuscript contained one paper (Winckler et al., 2018) that had not been accepted yet. This manuscript has now been accepted (doi: 10.1029/2018gl080211) and can be made available to the reviewers.

This study endeavors to tease out the differences in the local response to deforestation on surface temperature and near surface air temperature on global scales as derived from an Earth system model and several climate models from the CMIP5 archive. The study uses a clever approach to first estimate non-local effects by considering only non-deforested grid points and producing a map of non-local effects by interpolation on deforested grid points. The local effect is then the difference between the total signal (total change in temperature due to deforestation) and the non-local effect. The main findings are that 1) deforestation mainly results in a non-local cooling and drying of the lowest atmospheric level, T2m and Tsurf with warming in the tropical land regions, 2) local effects are more strong and heterogeneous at the surface, 3) in the mid-latitudes the local response to deforestation of Tsurf and T2m can be of different magnitudes and sometimes even opposite. Authors then also try to explain this opposite local response of Tsurf and T2m in the mid-latitudes but the reasoning does not come across very clearly and in my opinion should be revised with details. Overall, the study proposes a potential new statistical method (based on the author's previous work) to address some previously observed differences between the response to defor- estation of Tsurf and T2m. This is a very important research question pertaining to our understanding of the impacts of deforestation on regional climate. This study points out a very important distinction that should be made while interpreting results from datasets of surface temperature versus near surface air temperature. In this regard the study contributes to current knowledge significantly and so is worthy of consideration. However, several important questions regarding the methodology and physical inter- pretation of the results remain which need to be addressed. I would like the authors to comment on my questions with some further analysis if possible/needed as seen fit by the authors. My comments are rather minor but I recommend publication of the study after another round of revisions which I'll be happy to review.

We are happy that the reviewer considers our study to contribute to current knowledge significantly and is worthy of consideration.

1. ***This is probably outside the scope of the present study but one still questions - what is the mechanism that results in opposite responses of Tsurf and T2m in the mid- latitudes? Can any mechanism be generalized to all such land regions which show opposite responses of dTsurf and dT2m? Probably not because otherwise all land regions between 35 and 55 north as well as south would show the opposite response. The authors do provide an explanation using the model physics and parametrizations (Page 8, line 29) but it is hard to interpret the underlying physics from this argument. Also it is not clear from this argument why such an opposite response will be observed only in the mid-latitudes. I think it will be worthwhile for the authors to include any hypotheses about candidate mechanisms in the manuscript? A bit more explanation in the present manuscript***

is needed if the authors intend to explain this opposite response using the Richardson number, because the argument in its present form is not very clear.

This paragraph had obviously not been clear yet, see comments of the other reviewers. We now hypothesize in the middle of section 3.1 that 'Part of the difference in the response at the surface and near-surface air could be explained by averaging daytime and nighttime response and averaging the response in different seasons', and in the last sentence of section 3.1 that 'for both variables, the annual mean response then depends on the balance between the daytime and nighttime response, and the balance between the responses in different seasons'. Furthermore, we hypothesize that the way T2m is calculated in the MPI-ESM could cause the opposite response of Tsurf and T2m. In the last two paragraphs of section 3.1, we now discuss separately what one could expect in reality (e.g. stronger near-surface vertical mixing during daytime), and how this is taken into account in the model's calculation, separately for Tmax and Tmin.

2. ***a) The cross product between dTlocal and dTnonlocal have been neglected based on some analysis by previous studies. But there are other non-local factors that can impact and couple with dTlocal, for example precipitation changes due to circulation changes corresponding to a particular pattern of deforestation can bring about changes in Tsurf via the surface energy budget. These changes will be counted as non-local because they are not a direct consequence of local deforestation. So this component of dTsurf should be accounted for in the non-local dTsurf which is estimated using neighboring grid points. But the neighboring grid points could have an entirely different land cover which could result in a nonrepresentative non-local dTsurf at deforested grid points - because the surface energy balance in these grid points will be different due to different vegetation types.***
b) So the effect of such a dTsurf can not be obtained from interpolation from neighboring points. How are such non-local effects from changes in variables other than Tsurf, T2m and Tair considered in the methodology?
c) Do the authors think such cross terms will also be negligible as is the case with dTlocal and dTnonlocal? If so can that be explicitly shown?

   a) For our method it does not matter whether other large-scale quantities (besides temperature) undergo changes. For the case of precipitation, we have demonstrated this explicitly in (Winckler et al., 2017a) where in Fig. 3c it can be seen that large-scale deforestation (7 of 8 grid boxes) substantially influences nonlocal changes in precipitation, but this has little influence on the resulting local effects on surface temperature (Fig. 2*a* and *b* in Winckler et al. (2017a)).
   b) Concerning the problem related to surface heterogeneity: To extract the local signal using our method, also the local conditions (albedo, roughness,...) must vary to a good approximation linearly across the neighboring grid cells. The error that is induced by the horizontal interpolation was assessed in a previous study by two simulations in which the deforestation pattern is shifted, and it was found that in most regions the interpolation error is much smaller than the local effects on surface temperature. (e.g., Fig. D2*e* in Winckler et al. (2017a)).
   c) Indeed there are interactions between the local and nonlocal signals. These interactions would be, in our case, lumped with the local effects. We now state this in section 2.1 and explain that the interactions were found to be small across a wide range of deforestation scenarios (Winckler et al., 2017a).

3. ***Page 6, line 7- I hope I understand this correctly – so land cover change is not the only difference between the historical and picontrol simulations? They differ also in terms of changing greenhouse gases? How is this difference going to feedback onto the impacts of deforestation in historical-picontrol? The authors say in the same paragraph that the method assumes that the greenhouse***

gases affect Tsurf and T2m in neighboring grid points in the same way but that will still cause a constant anomaly in the temperature values owing to the greenhouse gas increase. How is that taken care of in the algorithm so that it is similar to the simulations with MPI-ESM? No further analysis is needed. Only a more clear explanation of the experimental design with the CMIP5 models will suffice.

We are sorry that this was not clear in the original version. In section 2.3, we added the following: 'Linear regressions are fitted between temporal changes in temperature (the so-called predictand) and forest cover change (the so-called predictor) within a spatially moving window encompassing 5 x 5 model grid boxes. In the center of this moving window, the local effects are then defined as the temperature change for a hypothetical conversion of 100% forest into 100% open land (given by the slope of the regression) and is by construction largely independent of the changes due to the nonlocal greenhouse gas forcing and nonlocal deforestation effects (given by the y-intercept of the regression).'
The greenhouse gas forcing is a nonlocal forcing and therefore removed by this method. We think it is appropriate to implicitly put the CO2 forcing into the nonlocal effects because in Fig. 3 (for which this method is applied) we focus on the local effects only.

4. ***What type of spatial interpolation technique is used? is it linear or non-linear? Given that the variable field under study could be so heterogeneous (especially Tsurf), it seems that the interpolation technique can have significant impacts on the derived non-local and local fields which can impact the final interpretation of results.***

   We now state in section 2.1 that we use bi-linear interpolation. We are aware that the interpolation of both local and nonlocal effects may cause an interpolation error, but this interpolation error is comparably small in most areas (see Winckler et al. (2017a), Figs. D2 and D3 e) and f) for the interpolation errors in comparable deforestation scenarios but only 30-year simulations). Furthermore, we think that an interpolation error would affect both dTsurf and dT2m in a similar way and thus would not affect our conclusions regarding the *difference* between dTsurf and dT2m.

5. ***What would be the impact of topography and background climate on the interpolated local and non-local signals? Do the authors assume that because an extensive deforestation scenario is considered, the impact of elevation, terrain and background climate on the local and non-local effects is already represented in the deforested simulation?***

   Due to the heterogeneous topography of the land surface, the horizontal interpolation may introduce some error which is generally small (see answer to comment 4). A changing background climate can influence the local effects of deforestation to some extent (see Winckler et al. (2017b) for the change from present-day to RCP8.5 background climate). The only change in background climate in our simulations is caused by nonlocal effects; this change is substantially weaker than the greenhouse-gas-induced change in RCP8.5, so we think that local deforestation effects are not substantially influenced by changing background climate in our simulations.

6. ***As I understand the deforestation in the MPI-ESM simulations has a regular pattern (3 of 4 grid boxes). Although there is nothing intrinsically wrong in choosing such a deforestation pattern, but there is evidence from previous studies that regular deforestation patterns can trigger climatologically important mesoscale effects. Could the chosen deforestation pattern and any subsequent mesoscale effects have an impact on the simulated local dTsurf? Only an insight from the authors***

is requested without any additional analysis.

We think that such mesoscale effects are substantially smaller than local/nonlocal dTsurf itself. First, if changes in mesoscale circulations were important (e.g., increased convection over forest, increased subsidence over grass), we would for example expect a reduction in precipitation for the local effects and an increase in precipitation in the nonlocal effects, or the other way round. But this does not seem to be the case; Precipitation is reduced both locally and non-locally (Winckler et al., 2017a). Second, if changes in mesoscale circulations were important for local dTsurf, we would also expect to see the regular spatial pattern both in the local and nonlocal effects. This does not seem to be the case: In a deforestation scenario with only 1 of 8 grid boxes are deforested (Fig. D1b in Winckler et al. (2017a)), the nonlocal effects are equally strong in grid boxes that are directly adjacent to a deforestation grid box and grid boxes that are only surrounded by other no-deforestation grid boxes.

7. ***Were there any apparent differences in conclusions due to the use of a coupled dynamic ocean model versus the previous studies which used prescribed SSTs? In other words, does a dynamic ocean have a substantial role in deciding the local dTsurf and dT2m responses studied here? I guess a dynamic ocean would be more important for deciding the non-local response. Does this study in conjunction with previous studies throw some light on the role of the ocean in deciding the local and non-local response?***

   The reviewer is right that a dynamic ocean influences mainly the nonlocal effects: in accordance with (Davin and de Noblet-Ducoudre, 2010), most ocean regions show a slight deforestation-induced cooling following large-scale deforestation (their Fig. 3*a*, our Fig. 1) which probably feeds back on the background climate over land regions and causes the nonlocal effects over land to be slightly more cooling/less warming compared to the nonlocal effects in simulations with prescribed sea surface temperatures (see (Winckler et al., 2017a) Fig. D2 and D3 b) for comparable deforestation scenarios). This change in background climate could potentially also affect the local effects. However, also with an interactive ocean the local effects are largely insensitive to the areal extent of deforestation (Winckler et al., 2018), suggesting that the change in background climate, caused even by large-scale deforestation, is too small to substantially affect the local effects on surface temperature.

8. ***Page 6, line 25 – why is the non-local effect cooler and drier?***

   The first paragraph of section 3.1 now contains a more detailed explanation. The atmosphere becomes cooler and drier because locally deforestation reduces the input of sensible and latent heat from the surface into the atmosphere, see also (Winckler et al., 2018).

9. ***When comparing MPI-ESM results with CMIP5 models the authors point out that the similarities in the results could be due to the similarities in the way models estimate T2m (Page 11, line 14). Could there be other ways to test whether the results obtained are independent of the model parametrizations? Could this methodology be repeated with some observed/reanalyzed climate time scale global datasets of Tsurf and T2m? Such an analysis need not necessarily be included in the present manuscript but it will be helpful to know author's insights about using observed data with the same methodology. What would be the challenges in such an analysis?***

   It would be desirable to repeat the analysis with observation-based gridded datasets. However, we are not aware of any such dataset for T2m, which in reanalysis datasets is based on a model or semi-empirical formulas. Thus, the results would again depend on how T2m is calculated for day/night conditions and over different vegetation types in these formulas.

10. ***TECHNICAL COMMENTS***
    Page 11 line 7 – remove an extra 'the'

    Done.

11. ***Stippling showing significant differences on the difference maps (Figs 1 and 2) would help.***

    We added stippling for grid boxes where results are not significant at a 5% level according to a student t-test accounting for lag-1 autocorrelation.

12. ***Latitude markers on all maps will be helpful.***

    We added latitude markers on all maps.

References

Davin, E. L. and de Noblet-Ducoudre, N. (2010). Climatic impact of global-scale deforestation: radiative versus nonradiative processes. *Journal of Climate*, 23(1):97–112.

Winckler, J., Reick, C. H., Lejeune, Q., and Pongratz, J. (2018). Nonlocal effects dominate the global mean surface temperature response to the biogeophysical effects of deforestation. *Geophysical Research Letters*.

Winckler, J., Reick, C. H., and Pongratz, J. (2017a). Robust identification of local biogeophysical effects of land-cover change in a global climate model. *Journal of Climate*, 30(3):1159–1176.

Winckler, J., Reick, C. H., and Pongratz, J. (2017b). Why does the locally induced temperature response to land cover change differ across scenarios? *Geophysical Research Letters*, 44:3833–3840.

Response to reviewer 2 of the paper entitled
"Different response of surface temperature and air temperature to deforestation in climate models"
Ref.: esd-2018-66

We would thank the reviewer for the time he/she devoted on reviewing the manuscript, and for his/her helpful comments.

Below are the reviewers comments (***bold italic font***) and our responses to each point (normal font). All line numbers that we provide in our responses refer to the revised version of the manuscript in which track changes are not shown.
The original manuscript contained one paper (Winckler et al., 2018) that had not been accepted yet. This manuscript has now been accepted (doi: 10.1029/2018gl080211) and can be made available to the reviewers.

In this paper, the authors evaluate how the land cover change response differs for surface temperature relative to air temperature in observations and models. This paper provides important clarification in terms of how these two different temperatures respond to land cover change with observations indicating that changes in surface temperature are roughly twice as strong as they are for air temperature. Models show a varying amount of agreement with the observations. The assessment of local versus nonlocal responses is less developed and is less likely to be the 'final word' on this topic, but I believe the nonlocal results are still worthy of publication. The paper is generally well-written (though it could use another full edit) and the figures are clear. I recommend the paper for publication pending minor revisions as outlined below:

We are happy that the reviewer thinks our results are worthy of publication.

1. ***Definition of local: The authors use the term local to refer to responses to deforestation within the same grid cell where the deforestation occurs and nonlocal changes to situations where deforestation has effects that extend beyond the deforested region. This is a reasonable definition, but it's worth noting that several recent studies have looked at even more local responses by examining the sub-grid responses within a grid cell (e.g., forested vs cropland). Perhaps it would be helpful to note the difference in definition and to cite a few of these studies (e.g., Malyshev et al., 2015, Schulz et al., 2016, Meier et al., 2018).***

   It is indeed important to clarify differences to these previous studies. In the last paragraph of section 2.1, we now cite these studies and shortly discuss differences in the definitions of local effects.

2. ***P.1, Line 17: Not sure I agree with the statement 'Much less considered are the climate changes'. Researchers have been investigating the climate impacts of deforestation for decades.***

   We corrected the respective text. Now: 'In addition, changes in forest cover can cause a warming or cooling,...'

3. ***P.2, Line 34: For clarification, consider changing: 'the local effects have to be isolated from the climate model results' to 'the local effects need to be disaggregated from the nonlocal effects when analyzing climate model results.'***

   We changed the text accordingly (with 'separated' instead of 'disaggregated').

4. ***P.3, Line 26. Can you provide a rationale for the method of removing forest in 3 out of 4 grid cells? Why not 2 out of 4 or 1 out of 4 or 5 out of 6? Would be helpful to be able to refer to the deforestation map, either as a figure in the main text or as supplemental material.***

   We now acknowledge (last paragraph of section 2.1) that the choice of 3 of 4 grid cells is to some extent arbitrary, but the local effects within a grid cell are largely insensitive to this choice (Winckler et al., 2017a). We now provide the deforestation map in Fig. S1.

5. ***P.5, Line 24. It's not totally clear to me how T2m is derived from S2m using eqn. 1. Equation 1 describes how to calculate Szaero, not S2m.***

   We now state that $z_{aero} = 2\text{m} + d + z_0$ has to be used in equation 1 in order to derive T2m.

6. ***P.5, Line 22: Change 'Different functions gamma are used' to 'Different functions for gamma are used'. Line 27: An extra 'and' in this line.***

   Thanks, corrected.

7. ***P.6, Line 26: This sentence confused me at first because I had forgotten about the way the global-deforestation run was done (i.e., with 3 out of 4 gridcells deforested). Please clarify. Seems possible that what you mean is actually 'large-scale' deforestation rather than global-scale.***

   We changed 'global-scale' to 'large-scale'.

8. ***Figure 1. Seems like some level of significance is needed here or at the very least selection of a color scale that doesn't imply a near-global signal from deforestation (i.e., colors everywhere).***

   We added stippling to indicate where results are not significant at a 5% level according to a student t-test accounting for lag-1 auto-correlation (Zwiers and von Storch, 1995).

9. ***P.11, line 5: Should probably note that CCSM4, CESM1-CAM5 and NorESM1 all share the same land model, CLM4).***

   I added this remark, thanks.

10. ***P. 11, line 17. I don't think this is an assumption, this is a result of your analysis. There is no 'assumption' that Tatm does not respond to deforestation.***

    I changed the phrasing, thanks.

11. ***12. P.12, line 26: Personally, I don't think the comment about carbon cycle feedbacks and the fact that they are non-local is necessary. First, this is stating the obvious. Second, this paper is about biogeophysical impacts.***

    This statement may be obvious for experts on deforestation effects in climate models, but possibly not for the broad audience of ESD. We would like to keep this statement to make non-experts aware that the biogeophysical effects (for which dT seems to differ especially for the local effects) are only one part of the deforestation effects, and that the other part, the carbon effects, can be expected to act essentially nonlocally.

Malyshev, Sergey, et al. "Contrasting local versus regional effects of land-use-change- induced heterogeneity on historical climate: Analysis with the GFDL Earth System Model." Journal of Climate 28.13 (2015): 5448-5469.

Meier, R., Davin, E. L., Lejeune, Q., Hauser, M., Li, Y., Martens, B., et al. (2018). Evaluating and improving the Community Land Model's sensitivity to land cover. Bio- geosciences, 15(15), 4731-4757. https://doi.org/10.5194/bg-15-4731-2018

Schultz, N.M., X. Lee, P.J. Lawrence, D.M. Lawrence, L. Zhao, 2016: Assessing the use of sub-grid land model output to study impacts of land cover change. JGR., 121, 6133-6147, DOI: 10.1002/2016JD025094.

References

Bright, R., Cherubini, F., and Str\omman, A. H. (2012). Climate impacts of bioenergy: Inclusion of carbon cycle and albedo dynamics in life cycle impact assessment. *Environmental Impact Assessment Review*.

Schultz, N. M., Lawrence, P. J., and Lee, X. (2017). Global satellite data highlights the diurnal asymmetry of the surface temperature response to deforestation. *Journal of Geophysical Research: Biogeosciences*, 122(4):903–917.

Winckler, J., Reick, C. H., Lejeune, Q., and Pongratz, J. (2018). Nonlocal effects dominate the global mean surface temperature response to the biogeophysical effects of deforestation. *Geophysical Research Letters*.

Winckler, J., Reick, C. H., and Pongratz, J. (2017a). Robust identification of local biogeophysical effects of land-cover change in a global climate model. *Journal of Climate*, 30(3):1159–1176.

Winckler, J., Reick, C. H., and Pongratz, J. (2017b). Why does the locally induced temperature response to land cover change differ across scenarios? *Geophysical Research Letters*, 44:3833–3840.

Zwiers, F. W. and von Storch, H. (1995). Taking serial correlation into account in tests of the mean. *Journal of Climate*, 8(2):336–351.

Response to reviewer 3 of the paper entitled
"Different response of surface temperature and air temperature to deforestation in climate models"
Ref.: esd-2018-66

We would thank the reviewer for the time he/she devoted on reviewing the manuscript, and for his/her helpful comments.

Below are the reviewers comments (***bold italic font***) and our responses to each point (normal font). All line numbers that we provide in our responses refer to the revised version of the manuscript in which track changes are not shown.
The original manuscript contained one paper (Winckler et al., 2018) that had not been accepted yet. This manuscript has now been accepted (doi: 10.1029/2018gl080211) and can be made available to the reviewers.

1. ***General Comments***
The research described in this article addresses an interesting topic – how deforestation affects various measures of temperature, as calculated by global climate models. Overall, I thought the results were well presented, but I had some issues with the way the paper was written, which led to some confusion on my part that required repeated re-reading. Some important ideas were glossed over (e.g., deforestation leading to reduced longwave forcing from above), and I had to infer (possibly incorrectly) some cause-and-effect mechanisms. This will require more interpretation of the results than is presented here.

   We are happy that the reviewer is interested in the topic and the results are overall well presented. We see (also in the other reviewers' comments) that some more explanations are needed, so we improved the presentation of some ideas and mechanisms (see answers to the specific comments).

2. ***Specific Comments***
Page 2 Line 13: The 2 effects often associated with deforestation are albedo increases (which cool the surface) and a reduction in transpiration (which reduces the latent heat flux, forcing the sensible heat flux to rise and increasing the surface temperature). Is it the balance between these competing effects that depends on latitude, leading to cooling at some latitudes and warming at others?

   The reviewer is right that the change in surface temperature depends on the balance between these competing effects. We now refer to the study of Bright et al. (2012) which highlights the different contribution of radiative and nonradiative effects at different latitudes (their Fig. 3).

3. ***a) Page 2 Line 24: I'm confused by the way the 'forest world' was created. I understand how forest was placed in areas where it existed in pre-industrial times (but currently does not). Figure 1, however, shows strong local effects in the Sahara and Gobi deserts. Was there any difference in the local forcing at these locations? A map of what the vegetation in the forest world looks like (along with the 34 world) would be helpful.***
b) Page 2 Line 26: I'm not sure what 'three of four grid boxes' means. Were 3 out of every 4 forested ares randomly selected to be deforested, or was some kind of pattern used?

   a) We now provide a map (Fig. S1) showing which grid boxes were deforested (in a regular spatial pattern), The map also shows the fraction of vegetated areas in these grid box. In the forest world, forest is prescribed on all vegetated areas (e.g., 100% in most grid boxes where forest is present today,

but also on present-day grasslands) but close to 0% in areas with sparse present-day vegetation cover such as the Sahara or Gobi deserts. In the deforestation simulation, forests in the vegetated areas is replaced by 100% grasslands. The reviewer is right that there is some local change in surface temperature in the deserts although only a small fraction of the grid box was deforested. We hypothesize that this comparably large signal could be caused by the non-linearity in the response of surface temperature to changes in forest cover within a grid box (Winckler et al., 2017) (meaning that for low initial forest cover, small changes can have a large effect).
b) For the deforestation, a regular spatial pattern was used. In section 2.1 we now refer to the newly added deforestation map, see Fig. S1

4. ***Page 6 Line 4: They write 'nonlocal effects strongly depend on the areal extent and spatial distribution of deforestation'. I'm assuming that the deforestation patterns differ among the different climate models, which is why it is impractical to compare nonlocal effects between the different GCMs, correct?***

   We removed this point because it is not essential and it would require substantially more explanation to clarify.

5. ***Page 6 Line 25/26: I'm interpreting this as follows: deforestation leads to a global reduction in temperature and humidity (due to the increases in albedo and decreases in evapotranspiration?), and this leads to more longwave escaping to space and less coming from above. Is this correct, or do changes in cloud cover play a role? If the former, it should be stated more clearly.***
   Page 6 Line 27: The pattern of nonlocal effects in Fig. 1 needs some explanation. Why are the eastern Pacific Ocean currents warmer? And why are the forested areas in the Amazon and equatorial Africa warmer? How are they affected by their neighboring, deforested areas? Is this also due to changes in longwave forcing?
   Page 8 Line 4/5: Again, the idea here is that a local effect is propagated remotely by reducing humidity and allowing more IR to escape, correct? And if that is true, what is causing the nonlocal increases of the 3 temperature metrics in the Amazon and equatorial Africa? I'm assuming it is related to the dense forest in these areas, perhaps making the change due to deforestation more pronounced in these locations, but some explanation is needed.
   Page 8 Line 5: Now, it is stated that changes in atmospheric temperature and moisture are affecting longwave radiation. Is deforestation decreasing the global humidity, making the atmosphere more transparent to longwave?

   These four reviewer comments refer to the mechanisms and spatial patters for the nonlocal effects. The first paragraph in section 3.1 now provides a slightly more detailed explanation. At deforested locations, the input of latent and sensible heat into the atmosphere is reduced. This leads to a drier and cooler atmosphere, and this in turn reduces the longwave incoming radiation, also at locations that were not deforested (nonlocal effects). This explanation, as well as maps of the local changes in latent/sensible heat and nonlocal shortwave/longwave incoming radiation are included in the Supplementary Figures of Winckler et al. (2018) which is now also available to the reviewers. In the Amazon and in equatorial Africa the reduction of longwave incoming radiation is overcompensated by an increase in shortwave incoming radiation due to a reduction in cloud cover (see Figure 1 below).
   We feel that a more detailed analysis of the nonlocal effects, i.e. changes in the ocean circulation, goes beyond the scope of the current study.

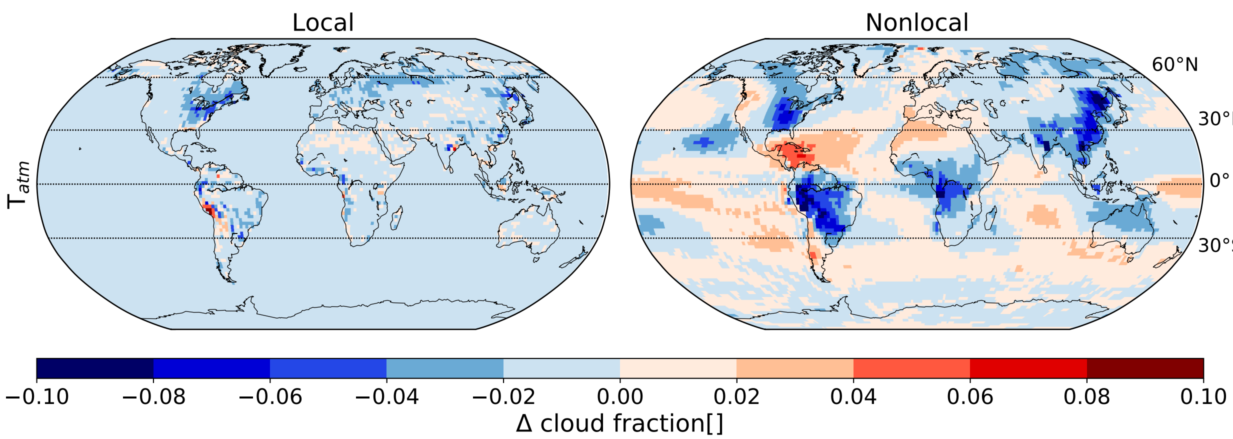

Figure 1: *Deforestation-induced annual mean changes in cloud cover in the '3/4' simulation using the MPI-ESM. The locations where cloud cover decreases for the nonlocal effects are co-located with regions with a nonlocal increase of incoming radiation (Fig. S6 in Winckler et al. (2018)).*

6. ***Page 8 Line 30-35:***
a) If 'atmospheric conditions are unstable', why do we not see convective overturning of the atmosphere? This would eliminate the vertical gradient seen in Fig. S3b.
b) Also, how does reducing the roughness length increase instability?
c) I'm not quite following this explanation for the differences between Figs. S3a and S3b. First, Tsurf is shown to increase during the day and decrease at night. These are linked to changes in stability, and this leads to differences in the way T2m is calculated between night and day with Monin-Obukhov theory and Eq. 2. What is missing is an explanation of the changes in Tsurf, why they differ between day and night, and why the changes vary with latitude (Fig. 2). Are they related to changes in albedo, in evapotranspiration, or both? This seems to be the key driver for the local changes, and ultimately the nonlocal changes as well.
d) Additionally, invoking the parameterization in Eq. 2 as the explanation of why the T2m values don't change as much as the Tsurf values is not really explaining why it is happening. Exactly what physical mechanism is causing the 2m temperature to vary less?
e) Finally, this explanation of differing responses between Tsurf and T2m in summer and during the day is ultimately the reason that these 2 variables look different in the annual averages in Fig. 1, correct? And the way that local changes in Tsurf vary with latitude in Fig. 1 are because the changes in Tmin at the surface dominate at high norther latitudes, while the changes in Tmax dominate elsewhere, correct?

a) Indeed, during daytime we would expect potential air temperature to be similar for T2m and Tatm. We suggest two potential reasons for the temperature gradient in Fig. 3b): First, even without a vertical gradient in potential temperature we would expect a gradient in actual temperature due to the lapse rate. Second, the calculation of T_{2m} is based on semi-empirical formulas and does not explicitly account for the input of sensible heat from the surface or vertical mixing within the atmosphere.
b) In the new version of the paragraph, we don't mention surface roughness because this was obviously confusing. We hypothesize that reducing roughness length could increase daily maximum surface temperature by reducing the ability of the surface to transfer latent and sensible energy into the atmosphere. The surface would have to warm up more (compared to a rougher surface) in order to get rid of energy via longwave outgoing radiation (Stefan-Boltzmann-law). Consequently also the

gradient between the maximum temperature at the surface and the atmosphere could increase.
c) Why surface temperature responds differently for daytime and nighttime is an interesting question, but has already been investigated in previous studies (e.g., Schultz et al., 2017). We now refer to the previous studies also in these sentences.
d) In the last two paragraphs of section 3.1 we now provide a physical explanation of what would intuitively be expected and how the differences in near-surface stability between day and night are taken into account in the models' calculation of T2m.
e) We now hypothesize that part of the difference between the response of Tsurf and T2m can be explained by differences during daytime/nighttime and during the different seasons. We now also discuss in section 3.1 that the way T2m is calculated in the model may be important for explaining why the response of T2m and Tsurf can differ even e.g. for Tmax in JJA, see Fig. S9, and that the annual mean response depends on the balance between the daytime and nighttime response, and the balance between the responses in different seasons.

7. ***Technical Corrections***
Page 1 Line 5: The acronym MPI-ESM should be spelled out here.
Line 7: The phrase 'effects affect' is awkward, and should be revised.

   Corrected, thanks!

8. ***Line 11: It was already established that the authors were using the MPI-ESM, so what is this 'inter-model comparison' they mention now? A sentence explaining that existing model data from multiple GCMs was examined for comparison to the MPI-ESM results is needed.***
Page 3 Line 15: The 'wide range of climate models' needs more context. As in the abstract, a sentence explaining the idea should suffice.

   We added such a sentence in the abstract and the introduction.

9. ***Page 5 Line 27: The first sentence of Section 2.3 is confusing and should be rewritten. The phrase 'In order to. . ..other climate models,' is not needed, since it just states the same idea in the rest of the sentence.***
Page 6 Line 6: Change 'deforestation in the difference' to 'deforestation as the difference'.

   We changed the respective sentences.

10. ***Page 7 Figure 1: These are annual means, correct? If so, it should be in the caption.***

    Done.

11. ***Page 8 Line 23: The sentence 'Similarly as in the case. . .' should reference Fig. 2.***

    Done.

12. ***Page 11/12 Some information in the Discussions/Conclusions section was already included in the introduction.***

    We revised the introduction and discussions/conclusions to avoid repetition of information.

References

Bright, R., Cherubini, F., and Str\omman, A. H. (2012). Climate impacts of bioenergy: Inclusion of carbon cycle and albedo dynamics in life cycle impact assessment. *Environmental Impact Assessment Review*.

Schultz, N. M., Lawrence, P. J., and Lee, X. (2017). Global satellite data highlights the diurnal asymmetry of the surface temperature response to deforestation. *Journal of Geophysical Research: Biogeosciences*, 122(4):903–917.

Winckler, J., Reick, C. H., Lejeune, Q., and Pongratz, J. (2018). Nonlocal effects dominate the global mean surface temperature response to the biogeophysical effects of deforestation. *Geophysical Research Letters*.

Winckler, J., Reick, C. H., and Pongratz, J. (2017). Why does the locally induced temperature response to land cover change differ across scenarios? *Geophysical Research Letters*, 44:3833–3840.

Response to reviewer 4 of the paper entitled
"Different response of surface temperature and air temperature to deforestation in climate models"
Ref.: esd-2018-66

We would thank the reviewer for the time he/she devoted on reviewing the manuscript, and for his/her helpful comments.

Below are the reviewers comments (***bold italic font***) and our responses to each point (normal font). All line numbers that we provide in our responses refer to the revised version of the manuscript in which track changes are not shown.
The original manuscript contained one paper (Winckler et al., 2018) that had not been accepted yet. This manuscript has now been accepted and can be made available to the reviewers.

This paper 'Different response of surface temperature and air temperature to deforestation in climate models' by Johannes Winckler investigated the discrepancy in the temperature response to deforestation between climate model and observations, and how the deforestation impact differs among temperature variables. The question studied here is important to understand the impact of deforestation on temperature. The paper also presents some interesting new findings on this topic. Therefore, I think the paper is suitable for publication in Earth System Dynamics.

We are happy that the reviewer is interested in the topic and finds the paper suitable for publication in Earth System Dynamics.

1. ***Major comments:***
   a) I feel the manuscript needs to be edited to improve the language, especially for the use of preposition like 'the', and some sentences are difficult to understand.
   b) According to results of this study, is it possible to establish a relationship to link the impact on surface temperature and on near-surface air temperature to reconcile their differences (a statistical model or the ratio 0.5 found in the paper)?
   c) When analyzing the discrepancy, model uncertainty should be always kept in mind. How the results of this study would be affected by such uncertainty?

   a) The language was improved, we hope that the sentences are now easier to understand.
   b) We think that it's a good idea by the reviewer to develop a statistical model to derive the T2m response from the Tsurf response. However, this is a non-trivial task as this ratio may vary by location and season (e.g. Figs. S7 and S8; Fig. 3 is only for DJF/JJA in the northern mid-latitudes) and goes beyond the scope of our study. Although the models seem to agree that the ratio of dT2m:dTsurf is around 1:2 over the studied region and the considered seasons, the exact ratio between the response of T2m and Tsurf is still to some extent model specific (range for JJA: 0.35-0.66 excl. HadGEM2-ES, see Table S1).
   c) The reviewer is right that it is important to be aware of model uncertainties. In the last paragraph of section 3.2, we argue that the inter-model differences are large for dTsurf, but smaller for the ratio between dTsurf and dT2m.

2. ***P2 L30: It would be better to also provide the submitted manuscript (Winckler et al., 2018) to reviewers to facilitate the review.***

   We are sorry about the inconvenience in the first phase of the review process. The manuscript

(Winckler et al., 2018) is now published (doi: 10.1029/2018gl080211) and can be made available to the reviewers.

3. ***P2 L31: I think these studies compared nearby locations between forest and non-forest or between locations with and without deforestation.***

   We adjusted the text accordingly.

4. ***P2 L35: Please specify the different mechanisms here.***

   We now specify one sentence later that the local effects act predominantly via changes in turbulent heat fluxes, while the nonlocal effects act predominantly via changes in incoming radiation that reaches the surface (Winckler et al., 2018).

5. ***P3 L6-8 This sentence needs to be revised for clarity.***

   We removed this sentence which was obviously confusing and did not add much value.

6. ***P3 L16: add '. . . from CMIP5.'***

   We adjusted this sentence and included the 'CMIP5'.

7. ***P4: 'The local effects are thus the temperature changes that exceed the nonlocal temperature changes that are obtained by interpolation from nearby non-deforested grid boxes'. I don't understand this sentence.***

   We removed this sentence because it was obviously not clear, and it was anyway only meant to be a summary of what was explained above.

8. ***P4 L2.3 Better specify 'CMIP5' models***

   The title of section 2.3 is now 'Isolation of local effects across CMIP5 models'.

9. ***P5 L9: How about the 2m temperature in other models, is it defined in a similar way and thus have the similar problem?***
   As for 2m temperature from observation, is it the 2m above ground (within canopy), or 2m above canopy?

   We think that it is reasonable for climate models to use semi-empirical formulas based on Monin-Obukhov similarity theory (see last paragraph of section 3.2), and thus we expect that also in other models temperature is defined 2m above $d + z_0$ rather than 2m above the surface or canopy. Concerning the observations, we state in the discussions section (around p. 13, l. 19) that weather stations (i.e. in forest clearings) record temperatures at a height of between 1.2m and 2.0m above ground level while temperature at Fluxnet sites is typically recorded 2-15m above forest canopies.

10. ***P5 L31: Why only 30 years for the non-local effect? I realized that this is explained later. Maybe some rearrangements can be done for this.***

    Section 2.3 is now re-arranged such that first the '30 years' are introduced.

11. ***Figure 1: Since the transition latitude from warming to cooling is discussed in the paper, it would be useful to have a latitudinal averaged temperature response for different temperature variables (or in a separate figure).***

    We now provide zonal land averages of the responses of T2m and Tsurf in Fig. S2.

12. ***P8 L30-35. If the discrepancy is explained this way by Richardson number, it sounds like such discrepancy is a model-dependent artifact instead of actual phenomenon. The discrepancy can be seen in observations (e.g., Baldocchi 2013), suggesting it is not just the Richardson number reason. I guess that the differences in the magnitude of Tmin/Tmax and seasonal responses could play a role because they cancel out each other at the annual mean scale.***

    The reviewer is right that the magnitude of the Tmin/Tmax and seasonal responses are important to explain the annual mean response of Tsurf and T2m, we added this as the last sentence in section 3.1. However, we think that differences between Tmin/Tmax and between seasonal responses are not the only reason why Tsurf and T2m can respond differently; e.g., even for Tmax in JJA, in some regions T2m and Tsurf can show a different response (Fig. S9.)
    We re-wrote the last two paragraphs of section 3.1 (for Tmax and analogously for Tmin) to clarify that there is a plausible mechanism why T2m and Tsurf could respond differently in reality, and how this mechanism is implicitly accounted for in the calculation of T2m in the MPI-ESM.

13. ***P10: L11-13: I don't understand this sentence.***
    P10 L15: 'all but one model show a surface warming locally' this sentence may cause confusion.

    Both sentences were rewritten, we hope they are now more clear.

14. ***P11 L13-14. The 0.5 ratio is an interesting number. Is it applicable to section 3.1?***

    As can be seen in Fig. S2, this ratio varies with latitude, even when focusing on annual means. It seems plausible that this ratio may vary also with the considered season.

15. ***P12 L23: With the scale of deforestation in reality much smaller than the model simulation, the non-local effect is negligible and the local effect is dominant, this makes the climate model and observation more comparable.***

    The reviewer is right that the nonlocal effects in reality are much smaller than in our simulation '3/4'. We now clarify in the caption of Fig. 1 that the shown results refer to this simulation. Furthermore, we added in the text that the nonlocal effects are expected to be large especially in simulations of large-scale deforestation. This does not alter our statement that including the nonlocal effects causes an inconsistency in comparing the models and observations.

16. ***P13 L9-10: There is a possibility that this is due to in climate model uncertainty, we don't know if the model is able to perfectly simulate Tmax response. Model uncertainty needs to be taken into account when making this statement.***

    We replaced this sentence by the following:
    'Our results for the MPI-ESM suggest that the difference between T_{2m} and T_{surf} is particularly strong for mean daily maximum temperature (see Fig. 2). Further studies may investigate whether this is also true for other climate models and observation-based data-sets.'

17. ***A recent paper by Melo-Aguilar (2018) might be helpful.***

Thanks! The two suggested references are now included in the introduction.

Reference:
Baldocchi D, Ma S. How will land use affect air temperature in the surface boundary layer? Lessons learned from a comparative study on the energy balance of an oak savanna and annual grassland. Tellus B. 2013
Melo-Aguilar C, Gonzalez-Rouco JF, Garcia-Bustamante E, Navarro-Montesinos J, Steinert N. Influence of radiative forcing factors on ground – air temperature coupling during the last millennium: implications for borehole climatology. Clim Past. 2018;1583–606.

References

Winckler, J., Reick, C. H., Lejeune, Q., and Pongratz, J. (2018). Nonlocal effects dominate the global mean surface temperature response to the biogeophysical effects of deforestation. *Geophysical Research Letters*.

Different response of surface temperature and air temperature to deforestation in climate models

Johannes Winckler[1,2,3], Christian H. Reick[1], Sebastiaan Luyssaert[4], Alessandro Cescatti[5], Paul C. Stoy[6], Quentin Lejeune[7,8], Thomas Raddatz[1], Andreas Chlond[1], Marvin Heidkamp[1,2], and Julia Pongratz[1,9]

[1]Max Planck Institute for Meteorology, Hamburg, Germany.
[2]International Max Planck Research School on Earth System Modeling, Hamburg, Germany.
[3]Current affiliation: Laboratoire des Sciences du Climat et de l'Environnement, LSCE/IPSL, CEA-CNRS-UVSQ, Université Paris-Saclay, Gif-sur-Yvette, France.
[4]Vrije Universiteit Amsterdam, Faculty of Science, Amsterdam, the Netherlands.
[5]European Commission, Joint Research Centre, Institute for Environment and Sustainability, Ispra, Italy.
[6]Department of Land Resources and Environmental Sciences, Montana State University, Bozeman, MT, USA.
[7]Institute for Atmospheric and Climate Science, ETH-Zürich, Switzerland.
[8]Current affiliation: Climate Analytics, Berlin, Germany.
[9]Ludwig-Maximilians-Universität München, Munich, Germany.

Correspondence: Johannes Winckler(johannes.winckler@lsce.ipsl.fr)

Abstract. ~~Deforestation affects temperatures at the land surface and higher up in the atmosphere~~Temperatures changes following deforestation are well documented but considerable uncertainty remains concerning their precise value. Part of this uncertainty may be caused by the fact that different methods used to quantify temperature changes, i.e., satellite-based observations, in-situ observations, and climate models, consider different temperatures. Satellite-based observations typically register deforestation-induced changes in surface temperature, in-situ observations register changes in near-surface air temperature, and climate models simulate changes in both temperatures and the temperature of the lowest atmospheric layer. Yet a ~~focused analysis of how these variables respond differently to deforestation is missing. Here, this is investigated~~ consistent comparison of the response to deforestation for different temperature variables was missing. In this study the effects of deforestation on surface temperature, near-surface air temperature and lower atmospheric temperature are compared by analyzing the biogeophysical temperature effects of large-scale deforestation in the ~~climate model~~ Max-Planck-Institute Earth System Model (MPI-ESM~~,~~) separately for local effects (which are only apparent at the location of deforestation) and nonlocal effects (which are also apparent elsewhere). While the nonlocal effects ~~affect~~ influence the temperature of the surface and lowest atmospheric layer equally, the local effects mainly affect the temperature of the surface. In agreement with observation-based studies, the local effects on surface and near-surface air temperature respond differently in the MPI-ESM, both concerning the magnitude of local temperature changes and the latitude at which the local deforestation effects turn from a cooling to a warming (at 45-55° N for surface temperature and around 35° N for near-surface air temperature). ~~An~~ Subsequently, our single-model results are compared to model data from multiple climate models. This inter-model comparison shows that in the northern mid latitudes, both for summer and winter, near-surface air temperature is affected by the local effects only about half as ~~much compared to~~ strongly as surface temperature. ~~Thus, studies~~ This study shows that the choice of temperature variable has a considerable effect

on the observed and simulated temperature change. Studies about the biogeophysical effects of deforestation must carefully choose which temperature ~~they~~ to consider.

1 Introduction

Afforestation has been proposed as a tool to mitigate climate change globally (UNFCCC, 2011), mainly because forests can store large amounts of carbon (Luyssaert et al., 2008; Le Quéré et al., 2017). ~~Much less considered are the climate changes, be it cooling or warming, that are caused by~~ In addition, changes in forest cover can cause a warming or cooling via an alteration of the exchange of energy and water between the Earth's surface and the atmosphere, i.e. the so-called biogeophysical effects (Bonan, 2008). Earth System models have been employed to assess how these biogeophysical effects affect the temperature of the *surface* (e.g., Bala et al., 2007; Pongratz et al., 2010; Davin and de Noblet-Ducoudre, 2010; Boisier et al., 2012; Devaraju et al., 2015; Li et al., 2016) and the temperature of the *near-surface air* (usually air ~~at~~ temperature 2 m ~~)~~ ~~(e.g., Claussen et al., 2001; Gibbard et al., 2005; Findell et al., 2006; Pitman et al., 2009; Bathiany et al., 2010; de Noblet-Ducoudré et al.,~~ above zero-plane displacement height) (e.g., Claussen et al., 2001; Gibbard et al., 2005; Findell et al., 2006; Pitman et al., 2009; Bathiany . ~~Surface temperature matters for habitat and vegetative function (e.g., Chen et al., 1999; De Frenne et al., 2013) while near-surface air temperature is often considered to be more related to the temperature that humans perceive (e.g., Staiger et al., 2011).~~ The different temperature variables that are considered in studies about deforestation effects are relevant for different questions and applications. Satellite-based studies on changes in radiometric surface temperature provide important information about the biophysical mechanisms of surface energy partitioning and thereby surface-atmosphere interactions (Duveiller et al., 2018) . Compared to changes in surface temperature, changes in air temperature may be considered more relevant for human living conditions because of their importance e.g. for the perceived temperature (e.g., Staiger et al., 2011). Within- and below-canopy air temperature (which is not included in this study) is the most relevant variable for many organisms that live within forests (e.g., De Frenne et al., 2013). ~~The focus of this studyis the question~~ The coupling between ground temperature and air temperature is strongly influenced by the type of vegetation that covers the surface (Baldocchi, 2013; Melo-Aguilar et al., 2018), but it remains unclear whether surface temperature and near-surface air temperature respond differently to deforestation in climate models. This is the focus of the present study.

An answer to this question could help to reconcile apparent inconsistencies in observation-based studies on the effects of deforestation on surface temperature and air temperature. Studies based on satellite observations ~~(Li et al., 2015; Alkama and Cescatti, 2016;~~ investigated changes in radiometric surface temperature ~~which, with its heterogeneous emissivity (Jin and Dickinson, 2010), represents a combination of temperature of the vegetation and the soil (through gaps in the canopy). The studies based on satellite observations~~ resulting from deforestation (Li et al., 2015; Alkama and Cescatti, 2016; Duveiller et al., 2018). These studies reported that deforestation ~~leads to~~ results in a local cooling in the boreal regions (north of approx. 45-55°N) and a warming in lower latitudes, highlighting that the contributions from changes in surface albedo and other surface properties vary with latitude (Bright et al., 2017). Studies based on observations of air temperature from weather stations and Fluxnet towers (Lee et al., 2011; Zhang et al., 2014) also reported a deforestation-induced boreal local cooling and a warming for lower latitudes, but they indicated that the transition between cooling and warming is located further south (at approx. 35°N). It remains unclear whether part of this apparent inconsistency can be attributed to the different heights above the surface at which temperature changes are considered. In contrast to ~~the~~ observations, climate models allow ~~us~~ to assess the biogeophysical effects both on surface temperature, on near-surface air temperature, and temperature of the atmosphere within ~~one~~ a single consistent framework, ~~and thus climate models are suitable~~ rendering climate models suitable tools to investigate this question.

Both ~~the~~ air and surface temperature ~~can be influenced~~ are affected by local and nonlocal biogeophysical effects of deforestation. We define local effects as effects that are only apparent in deforested locations and nonlocal effects as effects that are also apparent in non-deforested locations ~~(Methods and Winckler et al., 2017)~~(see Sect. 2.1 and Winckler et al., 2017). Local effects can for example be caused by a redistribution of heat between the surface and the atmosphere (e.g., Vanden Broucke et al., 2015) while the nonlocal effects can be caused by advection (Winckler et al., 2018) or by changes in global circulation (Swann et al., 2012; Devaraju et al., 2015; Lague and Swann, 2016)~~or advection (Winckler et al., 2018). Here, we consider~~. In this study, local and nonlocal effects are analyzed separately for three reasons. First, the difference between local and nonlocal effects matters for decision makers: the local effects may be relevant for policies that aim at adapting to a warming climate locally because they link the climate effects to the areas where policies are implemented (Duveiller et al., 2018). The nonlocal effects are also relevant for international policies that aim at mitigating global climate change because the nonlocal effects may dominate the global mean biogeophysical temperature response to deforestation (Winckler et al., 2018). Second, the observation-based data-sets only record the local effects when comparing temperature between nearby locations with and without forest, or between locations with and without deforestation. The nearby locations share the same background climate, and thus the nonlocal effects cancel out when temperature differences between the locations are considered (Lee et al., 2011; Li et al., 2015; Alkama and Cescatti, 2016; Duveiller et al., 2018). For a consistent comparison to observation-based data-sets, the local effects ~~have to be isolated from the~~ need to be separated from the nonlocal effects when analyzing climate model results. The third reason to consider local and nonlocal temperature changes separately is that different mechanisms trigger local and nonlocal temperature changes (Winckler et al., 2017). If surface and air temperature respond differently to deforestation, it is unclear whether this difference arises from ~~the~~ mechanisms that trigger the local temperature changes ~~, the~~ (predominantly via changes in the turbulent heat fluxes (Winckler et al., 2018)), mechanisms that trigger the nonlocal temperature changes ~~, or~~ (predominantly via the incoming radiation that reaches the surface (Winckler et al., 2018)), or from both. A separate analysis of local and nonlocal temperature changes facilitates an investigation of the mechanisms that may cause a different response of surface and air temperature to deforestation.

Here, we investigate how deforestation in the MPI-ESM climate model affects surface and air temperature differently and analyze this separately for the local and nonlocal effects. ~~Thus, we emulate the deforestation effects on surface temperature as estimated from satellite data and~~

A previous study contrasted the response of surface temperature only with the response of near-surface air temperature ~~as estimated from in-situ measurements within a consistent framework. In a previous study it was noted that~~ and found mainly differences between surface and air temperature ~~response differ mainly~~ for the local effects (Appendix C in Winckler et al., 2017). We go beyond this previous study by additionally analyzing the effects on temperature in the lowest atmospheric layer and by using simulations with an interactive ocean ~~because this is essential to capture the full climate~~ which enables us to better capture the nonlocal temperature effects of deforestation ~~(Davin and de Noblet-Ducoudre, 2010). This previous study (Winckler et al., 2017) contrasted the response of surface temperature only with the response of near-surface air temperature, while here we additionally analyze the effects on temperature in the lowest atmospheric layer~~from the surface to the lower atmosphere (Davin and de Noblet-Ducoudre, 2010). To further analyze the mechanisms that are responsible for differences in these three temperature variables, we investigate the local effects separately for the response in mean daily minimum and maximum temperature. To test the robustness of our results for this particular climate model, we compare the simulation results of the MPI-ESM to existing simulation results from multiple climate models from the Climate Model Intercomparison Project CMIP5. In this inter-model comparison, we contrast the response of the local effects on near-surface air temperature and surface temperature~~across a wide range of climate models~~.

2 Methods

2.1 Simulations of large-scale deforestation in the MPI-ESM

Using the fully coupled climate model MPI-ESM (Giorgetta et al., 2013), the temperature response to deforestation at the surface, at 2 m and the lowest layer of the atmosphere are obtained from simulations of large-scale deforestation. 550 years of simulations are performed in T63 atmospheric resolution (about 1.9°) and the last 200 years (which are free of substantial trends in the investigated variables (not shown)) are used for the analysis. ~~Following the approach as in a previous study (Winckler et al., 2017), two~~ Two simulations are performed: a first simulation ('forest world') ~~with~~ prescribes forest plant functional types on ~~all~~ areas where vegetation is expected to have been present at pre-industrial times (i.e. forests do not exist in deserts~~etc.). These vegetated areas~~). Vegetated areas and their likely vegetation cover from a previous study (Pongratz et al., 2008) were reconstructed from potential vegetation based on remote sensing data (Ramankutty and Foley, 1999). In a second simulation forests are completely replaced by grasslands in three of four grid boxes in a regular spatial pattern (Fig. S1, equivalent to simulation '3/4' in a previous study (Winckler et al., 2018)). In both simulations, atmospheric CO_2 concentrations are prescribed at pre-industrial level in order to obtain only the biogeophysical effects of deforestation. The total~~(~~, i.e. local plus nonlocal~~)~~, biogeophysical deforestation effects are then computed as the differences (e.g., in temperature) between these two simulations.

Following the approach in Winckler et al. (2017), the total effects can be separated into the local and nonlocal effects of deforestation as follows:

$$\Delta T^{total} = \Delta T^{local} + \Delta T^{nonlocal} + \Delta T^{(local\times nonlocal)},$$

~~where ΔT^{total}~~

$$\Delta T_{total} = \Delta T'_{local} + \Delta T_{nonlocal}, \tag{1}$$

where ΔT_{total} are the temperature changes that are simulated at a deforested grid box and ~~$\Delta T^{(local \times nonlocal)}$ are~~ $\Delta T'_{local} = \Delta T_{local} + \Delta T$ includes both the local effects and possible interactions between local and nonlocal effects. ~~We neglect these interactions here because they~~ However, such interactions were found to be small ~~for~~ across a wide range of deforestation scenarios (Winckler et al., 2017), and in the following we refer $\Delta T'_{local}$ as 'local effects'. The nonlocal effects are determined from non-deforested grid boxes, where only the nonlocal effects are present. The nonlocal effects are spatially interpolated to the deforested grid boxes using bi-linear interpolation. The local effects at deforested grid boxes can thus be obtained by subtracting the nonlocal effects from the simulated total effects:

$$\cancel{\Delta T^{local} = \Delta T^{total} - \Delta T^{nonlocal}.}$$

$$\Delta T'_{local} = \Delta T_{total} - \Delta T_{nonlocal} \tag{2}$$

The local effects ~~are thus the temperature changes that exceed the nonlocal temperature changes that are obtained by interpolation from nearby non-deforested grid boxes~~ that are obtained this way are similar to the local effects that were obtained in previous studies by comparing temperatures in sub-grid tiles (Malyshev et al., 2015; Schultz et al., 2017; Meier et al., 2018). In contrast to their methods, the method that is applied in this study includes local feedbacks between surface and atmosphere leading e.g. to local changes in clouds or precipitation. In addition, the method used in this study allows to assess the local effects on the temperature of the lowest layer of the atmosphere (which in most models is not calculated separately for sub-grid tiles) and to assess nonlocal effects on temperature. The choice of deforesting three of four grid boxes is to some extent arbitrary; varying the spatial extent of deforestation influences the magnitude of the nonlocal effects on surface temperature (Winckler et al., 2018), but the local effects on surface temperature within a grid box are largely insensitive to deforestation elsewhere (Winckler et al., 2017). A detailed description and discussion of the separation approach can be found in Winckler et al. (2017).

2.2 Temperature of the surface, the lowest atmospheric layer, and near-surface air in the MPI-ESM

This study investigates the response of three types of temperature to deforestation in the MPI-ESM: surface temperature (T_{surf}), temperature of the lowest atmospheric layer (T_{atm}, in the following 'atmospheric temperature'), and near-surface air temperature (T_{2m}, called 'tas' in ~~the Climate Model Intercomparison Project~~ CMIP5 and in the following 'air temperature'). ~~These~~ Although these temperature variables are part of the standard output of climate model simulations, different models may calculate them differently. In the ~~following, we describe how their values are obtained~~ folllowing, details are provided on the calculations of these variables in the MPI-ESM.

The surface temperature T_{surf} in the MPI-ESM is determined by solving the surface energy balance equation in a bulk canopy layer. For simplicity this layer has a heat capacity that is independent of the vegetation type. This bulk canopy layer exchanges heat with deeper soil layers via the ground heat flux.

It is not possible to assign one geometrical height to the surface layer in the MPI-ESM because there is an internal inconsistency between the two different aspects that are involved in the process of solving the surface energy balance equation: the calculation of the surface radiative budget (absorption of solar radiation and emission of terrestrial radiation to the atmosphere) and the calculation of the turbulent heat fluxes (latent and sensible heat). From the perspective of the radiative budget, the surface is where this radiative budget is calculated (i.e. where the energy balance is solved). In the presence of vegetation this is somewhere in the canopy, but geometrically its exact height cannot be specified. From the perspective of turbulent fluxes, the geometrical height $d+z_0$ above the surface is where the wind speed would become zero in the wind profile based on Monin-Obukhov theory (Leclerc and Foken, 2014). Here, ~~z denotes the height above the ground~~ z_0 denotes the aerodynamic roughness length and d is the zero-plane displacement height. This d takes into account the displacement effect exerted by vegetation (Leclerc and Foken, 2014; Campbell and Norman, 1998). Geometrically the height $d+z_0$ may differ from the height where the radiative budget is calculated.

What does this inconsistency imply for the comparison between T_{surf} in the MPI-ESM and satellite-based products? For comparison with satellite observations only the radiative perspective is relevant – because satellites estimate temperature based on the emissions of terrestrial radiation. That the Monin-Obukhov theory provides a different definition of surface height must be considered as a special approximation to solve the energy balance, but has no consequences for comparison with satellite observations of surface temperature.

The 'atmospheric temperature' T_{atm} is defined here as the temperature of the lowest of the 47 atmospheric layers in the MPI-ESM (Stevens et al., 2013). The thickness of this layer is around 60 m (at 15°C), and the temperature is volume-averaged in this layer. This temperature is used for the calculation of the turbulent heat fluxes and T_{surf}.

The near-surface air temperature T_{2m} is estimated in the MPI-ESM as the air temperature 2 m above $d+z_0$. Because it is unclear (and irrelevant for the calculations) where within the canopy this $d+z_0$ is, a comparison of T_{2m} between the MPI-ESM and observations is challenging, especially in forests (see ~~Discussions~~Sect. 4). The MPI-ESM does not have a representation of within-canopy air temperature or separate temperatures of the surface and the vegetation canopy.

In the MPI-ESM, T_{2m} is obtained via a procedure based on Monin-Obukhov similarity theory that uses the values at the surface and the lowest atmospheric layer. This procedure employs dry static energy instead of temperature because dry static energy is a conserved quantity in an adiabatic process.

$$s_{z_{aero}} = c_p T_{z_{aero}} + g z_{aero}, \tag{3}$$

where ~~$s_{z_{aero}}$ and $T_{z_{aero}}$ are the dry static energy and temperature at the aerodynamic height $z_{aero} = z - d$,~~ c_p is the heat capacity of moist air, and g is the gravitational acceleration of the Earth, and $s_{z_{aero}}$ and $T_{z_{aero}}$ are the dry static energy and temperature at the aerodynamic height $z_{aero} = z + d + z_0$ where z is the height above the surface.

At 2 m above $d+z_0$, the dry static energy is then obtained as follows:

$$s_{2m} = s_{surf} + (s_{atm} - s_{surf})\,\gamma\left(\frac{2\,\mathrm{m}}{z_0}, R_i\right), \tag{4}$$

where γ is a nonlinear function based on Monin-Obukhov similarity theory with values ranging between 0 and 1 that depends on the roughness length z_0 and on the bulk Richardson number R_i, which is closely related to the temperature gradient

~~T_{surf}~~ $T_{surf}-T_{atm}$. Different functions for γ are used for near-surface neutral ($R_i \approx 0$), stable ($R_i < 0$), and unstable conditions ($R_i > 0$) (ECMWF Research Department, 1991, section 3.1.3). Note that both s_{surf} and s_{atm}, but also R_i and z_0 are affected by deforestation. After this procedure, T_{2m} is derived from s_{2m} using ~~equation 3~~ $z_{aero} = 2\text{m} + d + z_0$ and equation (3).

2.3 Isolation of local effects across CMIP5 models

~~In order to compare the results for the MPI-ESM with other climate models, the~~ The temperature response of ~~and~~ near-surface air and surface temperature to deforestation in the northern-hemisphere mid latitudes are compared across a wide range of climate models from CMIP5~~. For this comparison, we focus on the local effects for three reasons: first, the local effects exhibit a better signal~~: CanESM2, CCSM4, CESM1-CAMS, GFDL-CM3, HadGEM2-ES, IPSL-CM5A-LR, MPI-ESM-LR, and NorESM1-M. Given that the these models did not simulate the '3/~~noise ratio compared to the nonlocal effects (e.g., Lejeune et al., 2017). This is important because the climate variability can be large compared to the nonlocal effects for the short time spans (30 years) that are analyzed here (Winckler et al., 2018). Furthermore, climate variability is especially large in the mid-latitudes (Deser et al., 2012) that are analyzed here. Second, the nonlocal effects cannot be isolated from the analyzed set of all-forcing simulations (see below). Third, the local effects at one location are largely independent of deforestation elsewhere (Winckler et al., 2017) while the nonlocal effects strongly depend on the areal extent and spatial distribution of deforestation (Winckler et al., 2018).~~

~~We do not isolate the local effects for these models the same way as described in section 2.1 because this approach would have required repeating these simulations for every model.Instead, we isolate the local effects of deforestation in~~ 4' deforestation (see Sect. 2.1), we invoke the difference between 'historical' and 'piControl' simulations ~~from~~ to isolate the local temperature response from the CMIP5 ensemble (Taylor et al., 2012). The 'historical' simulations are subject to all forcings including changes in greenhouse gases and land use while the 'piControl' simulations are subject to constant boundary conditions and no forcings. To isolate the local effects of deforestation, we use a method that was already applied and validated on these simulations (Lejeune et al., 2018). This method assumes that ~~T_{surf} and T_{2m}~~ temperature in neighboring grid boxes can be affected differently by the local effects of deforestation, depending on the forest cover change in each grid box, whereas other climate forcings (like greenhouse gases, but also the nonlocal effects) influence neighboring grid boxes in a similar way. ~~The local effects are extracted by fitting linear regressions~~ Linear regressions are fitted between temporal changes in temperature (the so-called predictand) and forest cover change (the so-called predictor) within a spatially moving window encompassing ~~5x5~~ 5 x 5 model grid boxes. In the center of this moving window, the local effects are then defined as the temperature change for a hypothetical conversion of 100% forest into 100% open land (given by the slope of the regression) and is by construction largely independent of the changes due to the nonlocal greenhouse gas forcing and nonlocal deforestation effects (given by the y-intercept of the regression).

We consider here the difference between the last 30 years (1971-2000) of 'historical' simulations for which data in all models are available and 30 years of the pre-industrial control simulations (piControl), from which the temporal changes in both temperature variables and forest fraction since 1860 are computed. The 'historical' simulations consist of several ensemble members for each model, where each ensemble member experiences the same forcings but starts from different initial conditions. The moving-window method is applied to several combinations of ensemble members from the 'historical' simulations and time slices from the 'piControl' simulations for each model, and the number of analyzed ensemble members is shown in Table S1.

For this inter-model comparison, we focus on the local effects for two reasons: (1) The nonlocal deforestation effects cannot be isolated from the analyzed set of simulations because the nonlocal deforestation effects cannot be distinguished from nonlocal greenhouse gas forcing in these simulations. (2) The local effects exhibit a better signal/noise ratio compared to the nonlocal effects (e.g., Lejeune et al., 2017). This is important because the climate variability can be large compared to the nonlocal effects for the short time spans (30 years) that are analyzed here (Winckler et al., 2018). Furthermore, climate variability is especially large in the mid-latitudes (Deser et al., 2012) that are analyzed in the inter-model comparison.

3 Results

3.1 Different temperature response of surface and air temperature in the MPI-ESM

In the MPI-ESM, ~~global-scale deforestation (~~deforestation in three of four grid boxes ~~)~~ triggers substantial nonlocal cooling in most regions (Fig. 1). ~~Deforestation makes the atmosphere~~ This happens because deforestation locally reduces the input of latent and sensible heat from the surface to the atmosphere (Winckler et al., 2018). Thus, the atmosphere becomes cooler and drier (not shown), and this leads to a reduction of T_{surf} in many regions, mainly because of reduced longwave incoming radiation (Davin and de Noblet-Ducoudre, 2010; Winckler et al., 2018). The spatial pattern of these nonlocal effects is very similar for T_{surf}, T_{2m} and T_{atm}.

In contrast to the nonlocal effects, the local effects differ strongly between T_{surf}, T_{2m}, and T_{atm}. Deforestation strongly influences the local surface energy balance: the imposed changes in surface properties in the model (surface albedo, evapotranspirative efficiency and surface roughness) cause a surface warming for the local effects in most regions, except for the high northern latitudes where the local effects cause a surface cooling (Fig. 1). The changes in surface properties influence not only the local surface temperature but also the flux of sensible heat from the surface into the lower boundary layer (not shown). Intuitively one would expect that the change in sensible heat flux alters T_{atm}, e.g. an increased input of sensible heat into the atmosphere could raise the temperature of the atmospheric air above a deforested location. However, in our model results T_{atm} is largely unaffected by the local effects of deforestation (Fig. 1). We interpret this lack of local effects in T_{atm} as follows: the time needed for the lowest atmospheric layer to warm up due to the deforestation-induced increase in sensible heat flux is long enough for the heated air to be transported to higher atmospheric layers and the neighboring grid boxes. Due to the advection, the change in atmospheric temperature is hence not only seen in a deforested location but also in nearby grid boxes that are not deforested. Thus, this warming or cooling is accounted for in the nonlocal effects. In the nearby grid boxes, the change in atmospheric temperature and/or moisture can then influence also T_{surf} via changes in longwave incoming radiation (Davin and de Noblet-Ducoudre, 2010; Winckler et al., 2018), which could explain why the nonlocal effects are similar for T_{atm} and T_{surf}. While in T_{atm}, advection can lead to a direct exchange of heat between neighboring grid cells, the same is

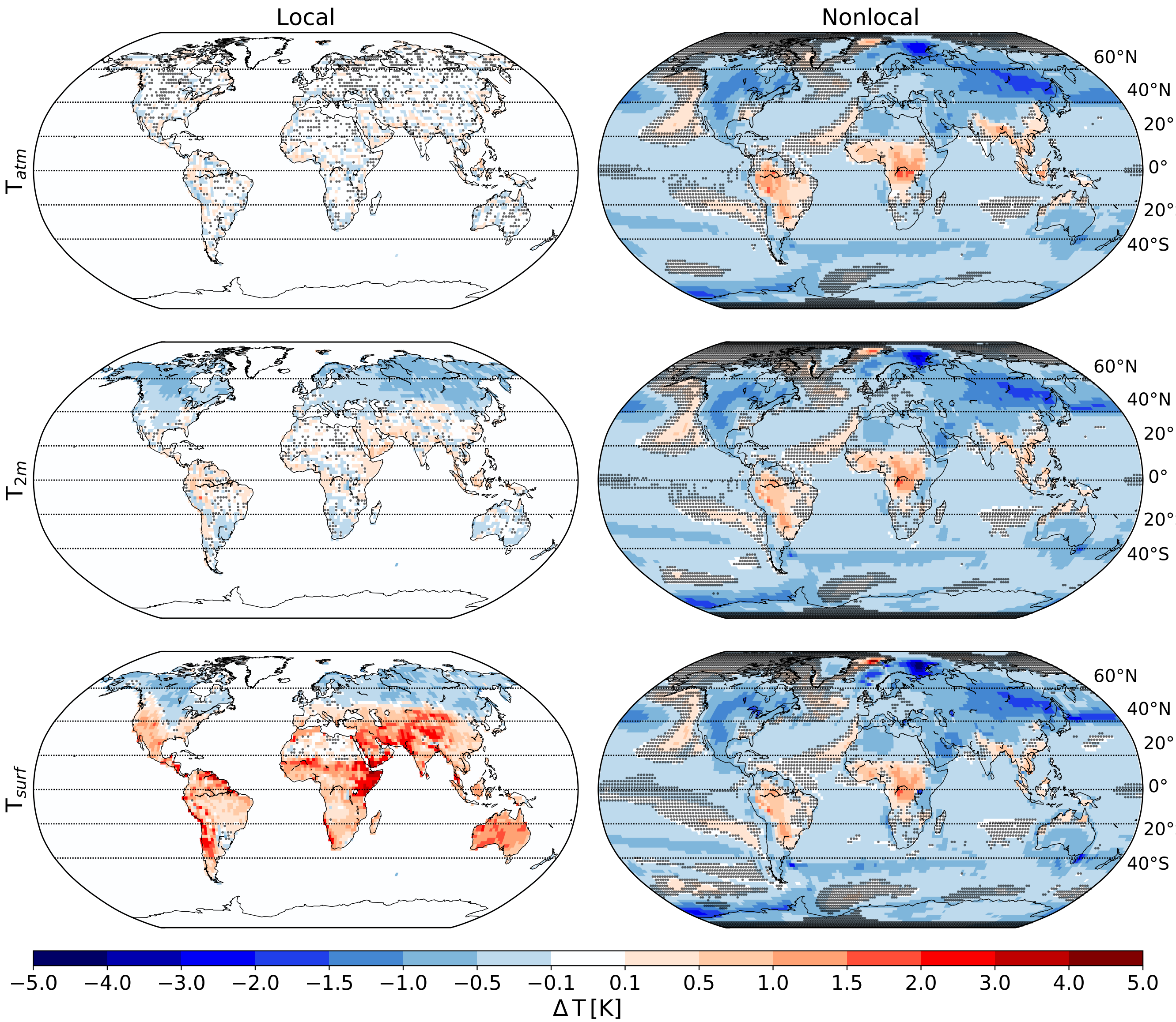

Figure 1. ~~Response~~ Deforestation-induced annual mean response of temperature in the lowest atmospheric layer (T_{atm}), near-surface air (T_{2m}), and at the surface (T_{surf}). Deforestation was applied to ~~deforestation~~three of four grid boxes (Fig. S1). Stippling indicates where results are not statistically significant at a 5% level for a Student's t test accounting for lag-1 autocorrelation (Zwiers and von Storch, 1995). Zonal averages are shown in Fig. S2.

not possible for T_{surf}; there is no direct horizontal exchange of heat between the surface of neighboring grid cells, and this difference (advection for T_{atm} but not T_{surf}) may explain why local effects can be seen in T_{surf} but not in T_{atm}.

Because the T_{2m} is an interpolation between T_{surf} and T_{atm}, we expected that also the local response of T_{2m} would lie in between the response of T_{surf} and T_{atm}. In a lot of regions this is the case, but in other regions, most notably those that show a cooling, the local effects on T_{2m} seem to cool more than T_{surf}, and in some regions even the sign differs between ΔT_{surf} and ΔT_{2m} (e.g. parts of the US and regions in the southern extra-tropics, Fig. ~~S1). What the~~ S3). The different response of T_{surf} and T_{2m} ~~means~~ in relation to the observation-based findings is discussed in ~~section~~ Sect. 4.

~~To~~ To better understand the apparent discrepancy between ΔT_{surf} and ΔT_{2m}, we separately analyze the local temperature response for boreal winter (DJF) and summer (JJA), and the response of mean daily minimum temperature (T_{min}, which approximately corresponds to nighttime conditions) and maximum temperature (T_{max}, which approximately corresponds to daytime conditions). For surface temperature, the response to deforestation locally differs strongly between DJF, JJA, T_{min}, and T_{max} values (Fig. 2). The northern-hemisphere DJF and the T_{min} surface temperatures ~~are strongly cooling~~ strongly cool for deforestation, while the JJA and T_{max} surface temperatures ~~are warming~~warm. This is qualitatively in good agreement with observation-based studies that show a local cooling in the boreal regions in DJF (Alkama and Cescatti, 2016; Bright et al., 2017; Duveiller et al., 2018) and in agreement with the local increase in the diurnal amplitude due to deforestation (Li et al., 2015; Alkama and Cescatti, 2016; Schultz et al., 2017). Similarly as in the case of long-term mean temperature (Fig. 1), T_{atm} locally ~~hardly responds~~ shows little response to deforestation, neither for DJF, JJA, T_{min}, nor T_{max} (Fig. 2).

For near-surface air temperature, the T_{max} response is substantially weaker, and in many areas of opposite sign, than for the surface, similar to the lowest atmospheric layer (land mean absolute changes for T_{max}: 1.62 K for the surface, 0.19 K for near-surface air, and 0.10 K for the lowest atmospheric layer). Our findings are in qualitative agreement with the findings of (Meier et al., 2018) (their Fig. 9), who found a strong deforestation-induced daytime surface warming and a moderate near-surface air cooling in many regions. On the contrary, most regions exhibit a strong T_{min} cooling of near-surface air temperature, similar to the T_{min} response of surface temperature (land mean absolute changes for T_{min}: 0.67 K for the surface, 0.48 K for the near-surface air, and 0.10 K for the lowest atmospheric layer). Part of the difference in the response at the surface and near-surface air could be explained by averaging daytime and nighttime response and averaging the response in different seasons. However, for instance T_{max} responds differently at the surface and near-surface air not only for annual mean T_{max}, but in some tropical/subtropical regions also for T_{max} during DJF and JJA (Fig. S9).

We interpret this as follows: During daytime ~~(during which~~ when T_{max} occurs~~)~~, the surface temperature is higher than the temperature of the lowest atmospheric layer (Fig. S2) ~~, which means that near-surface atmospheric conditions are unstable. Deforestation reduces the roughness length z_0 and~~ because the surface is heated by incoming radiation. In accordance with previous studies (e.g., Li et al., 2015), deforestation further increases surface temperature (Fig. 1) and thus also ~~atmospheric instability~~ the difference between surface temperature and the temperature of the lowest atmospheric layer (illustrated in Figure ~~S3 b), and this influences~~ S5b). Intuitively, we would expect that an increase in this difference would result in stronger vertical mixing of near-surface air and thus a near-constant potential temperature within the turbulent boundary layer. In the model's calculation of near-surface air temperature, this is implicitly accounted for: a deforestation-induced increase in surface temperature increases the difference between T_{atm} and T_{surf} and thus decreases the Richardson number R_i which enters the ~~Monin-Obukhov~~ similarity function for near-surface air temperature (γ in equation 4, see underlying report (ECMWF Re-

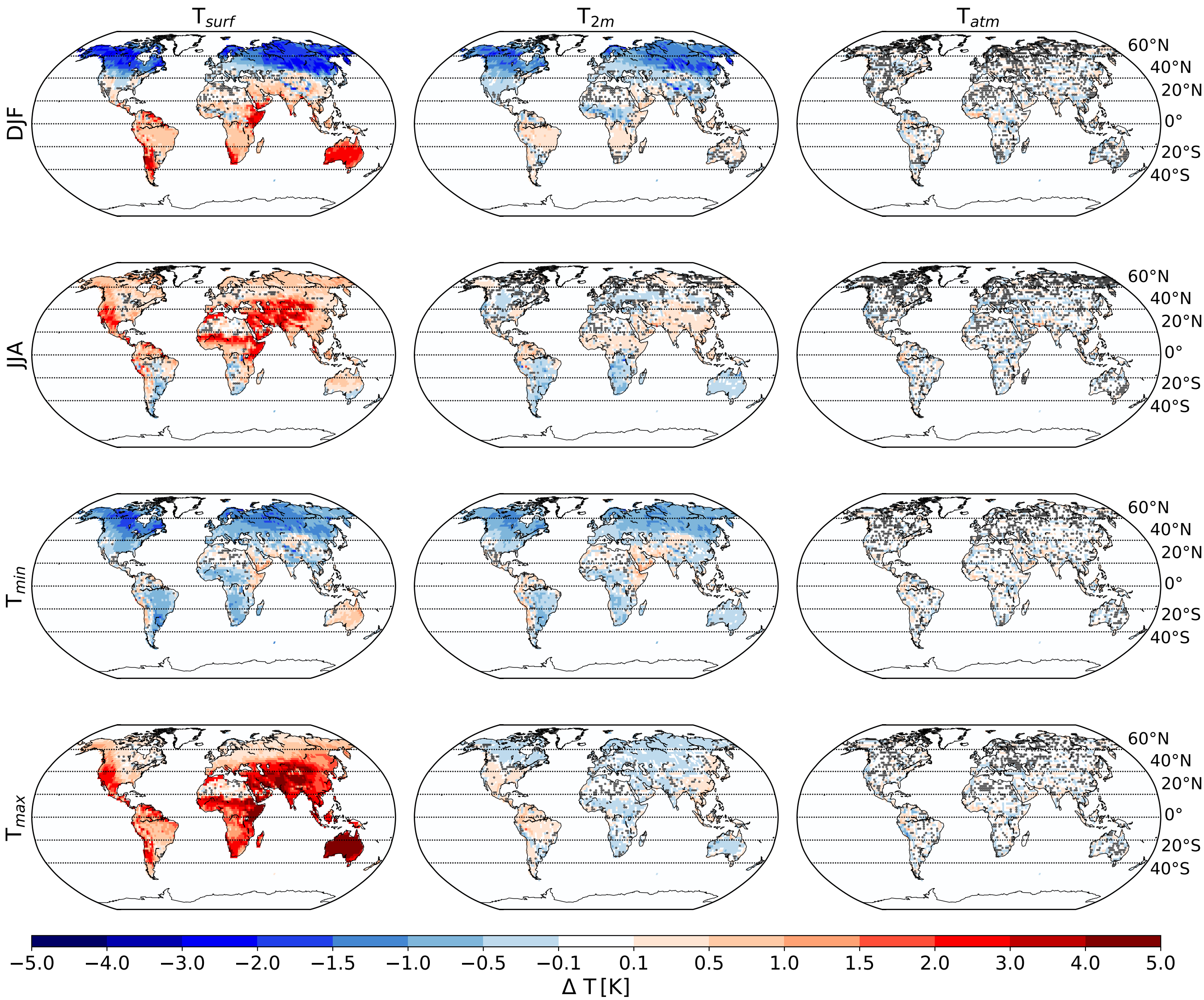

Figure 2. Seasonal and diurnal temperature response to the local effects of deforestation, separately for boreal winter (DJF) and summer (JJA), daily maximum (T_{max}) and minimum temperature (T_{min}). Stippling indicates where results are not statistically significant at a 5% level for a Student's t test accounting for lag-1 autocorrelation (Zwiers and von Storch, 1995).

search Department, 1991)) such that the calculated near-surface air temperature gets closer to the temperature of the lowest atmospheric layer. As a result, daily maximum near-surface air temperature in the model may decrease although surface temperature increases. ~~During nighttime (during which~~

During nighttime when T_{min} occurs~~), the near-surface atmospheric conditions may become neutral or stable near the surface~~ , the surface loses energy via outgoing longwave radiation, and thus the surface is often cooler than the overlying atmosphere (Fig. ~~S2), and thus a different Monin-Obukhov~~ S4). In accordance with previous studies (e.g., Schultz et al., 2017), deforestation further decreases surface temperature and thus also the difference between surface temperature and the temperature of the lowest atmospheric layer. Intuitively, we would expect that less vertical mixing occurs compared to daytime, and thus near-surface air temperature is more closely related to surface temperature. In the model's calculation of near-surface air temperature, this is implicitly accounted for by employing a different similarity function γ ~~is employed~~ in equation 4 (ECMWF Research Department, 1991), with the consequence that near-surface air temperature at deforested locations stays closer to surface temperature compared to daytime conditions (Figure ~~S3 a).~~ S5a). As a result, in most regions near-surface air temperature follows the deforestation-induced nighttime surface cooling but not necessarily the deforestation-induced daytime surface warming. For both variables, the annual mean response then depends on the balance between the daytime and nighttime response, and the balance between the responses in different seasons.

3.2 Different temperature response of surface temperature and air temperature across climate models

While the above results refer only to the MPI-ESM climate model, the local effects on T_{surf} and T_{2m} also differ in other climate models (Fig. 3). We analyze the local effects of historical deforestation and the average over mid-latitude areas (40-60° N) that experienced intense deforestation ($\geq 15\%$) since 1860. We choose the northern mid-latitudes for two reasons: ~~first, this is where historically~~ (1) This is where most historical deforestation happened, and regions with intense deforestation are required in the moving-window approach for ~~the isolation of~~ isolating the local effects across models (~~Methods~~see Sect. 2.3), and ~~second, it is interesting to analyze~~ (2) the mid-latitudes are a suitable test case because there the local effects on ~~temperature there because they~~ surface temperature have a different sign in the winter (DJF) and summer season (JJA)(Fig. 2).

In the considered areas, in most models (with the exception of CanESM2 and GFDL-CM3) ~~,~~ T_{surf} and T_{2m} respond similarly for changes in annual means ~~in the mid-latitude areas~~ (Fig. 3 a). This ~~includes~~ is also true for the MPI-ESM – ~~the different spatial patterns of warming and cooling for~~ T_{surf} and T_{2m} ~~discussed for the MPI-ESM in the previous chapter (Fig. 1 results in similar responses~~ respond similarly when averaged over the respective regions (mid-latitude areas (40-60° N) that experienced intense deforestation ($\geq 15\%$) since ~~1860.~~ 1860, Fig. S6). A difference in response between T_{surf} and T_{2m} becomes apparent also for the mid-latitudes ~~, however, when not annual mean, but~~ when analyzing seasons (DJF and JJA ~~seasons are considered separately~~separately) instead of annual means. Almost all of the tested models show substantial differences between T_{surf} and T_{2m} at seasonal scale (Fig. 3 b-c).

In JJA (Fig. 3c), all but one model show a surface warming locally, with the T_{surf} responding more strongly than T_{2m} by a factor of around two (Table S1). Only the HadGEM2-ES climate model is an outlier: there, T_{surf} responds to deforestation with a local cooling (-0.13 K), which is not in agreement with observation-based studies (Li et al., 2015; Alkama and Cescatti, 2016; Bright et al., 2017; Duveiller et al., 2018), and in the HadGEM2-ES T_{2m} cools even more strongly (-0.27 K) than T_{surf}.

In DJF (Fig. 3b), all but one model show a surface cooling locally, again with T_{surf} responding stronger than T_{2m} in most models. An exception is the CanESM2 model, which locally responds to deforestation with a strong T_{surf} warming and T_{2m} cooling. In some of the other climate models (CCSM4, CESM1-CAM5, NorESM1-M, all sharing the same land surface model CLM4), the T_{surf} cooling is approximately twice the cooling of T_{2m}, analogous to the JJA response. In other models (GFDL-

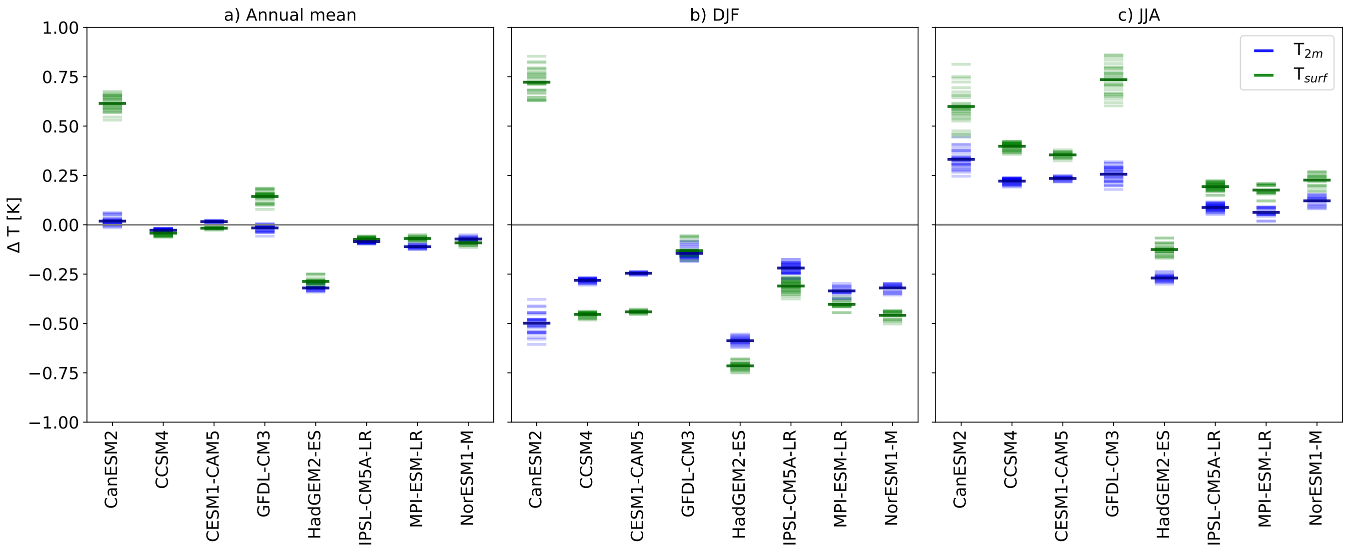

Figure 3. Local effects on near-surface air temperature (T_{2m}) and surface temperature (T_{surf}) for CMIP5 models. Values are averaged over mid-latitude areas (40-60° N) that experienced intense deforestation ($\geq 15\%$) since 1860. Positive values indicate a deforestation-induced warming. Each transparent marker denotes one combination of ensemble members from the 'historical' and 'piControl' experiments, respectively. The solid markers denote the mean values. The corresponding maps are shown in Figs. ~~S4-S6~~S6-S8. The local effects are isolated as in the study by Lejeune et al. (2018).

CM3, HadGEM2-ES, IPSL-CM5A-LR, MPI-ESM-LR), the ~~the~~ two variables respond more similarly in DJF compared to JJA.

Overall, the inter-model comparison suggests that the different response of T_{surf} and T_{2m} is not specific to the MPI-ESM model. In agreement with previous studies (Pitman et al., 2009; Boisier et al., 2012; de Noblet-Ducoudré et al., 2012; Lejeune et al., 2017), the inter-model spread in the temperature response in Fig. 3 is large (e.g., in JJA inter-model (excluding the HadGEM2) standard deviation 0.20 K, inter-model mean 0.38 K). However, the investigated models agree better concerning the ratio between the T_{2m} and T_{surf} response (JJA inter-model (excluding the HadGEM2) standard deviation 0.11, inter-model mean 0.50). Both for DJF and JJA (Table S1), and for most of the investigated models, the ratio of changes in T_{2m} and T_{surf} of 0.5 (range 0.35-0.65, excluding HadGEM2) is largely independent of the magnitude and sign of the surface temperature response. ~~Assuming that deforestation does locally not affect T_{atm}, the~~ The temperature response of T_{2m} is between zero and the response of T_{surf} with a ratio that depends on the exact way in which T_{2m} is calculated in the respective models (but most likely all models use a Monin-Obukhov approach). Further studies may investigate ~~the validity of the assumption that T_{atm} locally does not respond to deforestation, as well as~~ to what extent the calculation of T_{2m} differs across models~~and how this influences the deforestation response~~.

4 Discussion and conclusions

This study shows that in climate models, surface temperature (T_{surf}) and near-surface air temperature (T_{2m}) respond differently to deforestation. In the MPI-ESM, the nonlocal response (present also in locations that were not deforested) of T_{surf} and T_{2m} is similar, while their local response (present only in locations that were deforested) differs. In the northern mid- and high latitudes, the annual mean local cooling of T_{2m} can be stronger than the local cooling of T_{surf}, but in most regions T_{surf} responds stronger than T_{2m}. Across most models, the local effects of deforestation on T_{surf} and T_{2m} in the mid-latitudes differ by a factor of two in both investigated seasons.

This study illustrates that the conclusions concerning the effects of deforestation can depend on the considered temperature measure. ~~In observation-based studies, the magnitude and sign of deforestation effects can differ depending on the temperature measure; for instance, satellite–based studies on radiometric surface temperature (e.g., Li et al., 2015; Alkama and Cescatti, 2016; Duveille found that the local effects of deforestation turn from a cooling in the boreal regions to a warming further south at between 45-55°N (the latitudinally averaged local temperature effect at 50°N is about -0.5 K to 0.5 K, see Fig. 1 in the study by Winckler et al. (2018)). On the other hand, in-situ–based studies on T_{2m} found that the transition from warming to cooling is located much further south, at around 35°N, and that deforestation at 50°N leads to a cooling of around -1 K (e.g., Lee et al., 2011; Zhang et . These~~ The differences in magnitude and pattern between Δ T_{surf} (e.g., Li et al., 2015; Alkama and Cescatti, 2016; Duveiller et al., 2018) and Δ T_{2m} (e.g., Lee et al., 2011; Zhang et al., 2014) obtained from observation-based studies largely agree with our findings (more cooling for T_{2m} than for T_{surf} in the mid-latitudes for the local effects in the MPI-ESM ~~, see Fig~~(see Figs. 1 and S2) and thus our results make it seem plausible that the consideration of different temperature measures can explain some of the discrepancies between the satellite-based and in-situ–based studies. A consistent comparison between satellite–based and in-situ–based studies can be challenging because they may report different variables. ~~Satellite-based~~ Because of the heterogeneous emissivity of the land surface (Jin and Dickinson, 2010), satellite-based data-sets usually ~~reported~~ report changes in radiometric surface temperature, which ~~is~~ represents a combination of temperature ~~of~~ at the top of the vegetation and the soil (through gaps in the canopy). Satellite-based direct estimates of air temperature (based on the intensity of upwelling microwave radiation from atmospheric oxygen) are available only for broad vertical layers of the atmosphere and at coarse spatial scale (Von Engeln and Bühler, 2002). Instead of direct observations, air temperature was derived from surface temperature by empirical methods (Alkama and Cescatti, 2016) or process-oriented models (i.e. by solving the surface energy budget) (Hou et al., 2013). More direct observational investigations on the effects of deforestation on air temperature were based on recordings from weather stations and Fluxnet towers, which measure temperature at different heights. For instance, weather stations, e.g. in forest clearings, recorded temperatures at a height of between 1.2 and 2.0 m above ground level (WMO, 2008) while Fluxnet sites recorded temperatures typically 2-15 m above forest canopies (Lee et al., 2011; Zhang et al., 2014). The different measurement height may lead to systematic differences because of the steep vertical temperature profile that develops near the surface under stable atmospheric conditions (e.g. at night) especially over open land (Schultz et al., 2017). In contrast to satellite-based products, which are available at a high spatial resolution, the spatial distribution of Fluxnet towers and weather stations is biased toward developed countries and there is a relatively poor geographical coverage of rural areas in developing countries where deforestation has occurred recently (Hansen et al., 2013). To perform a meaningful comparison, near-surface air temperature would have to be available at the same height above canopy top (preferably multiple heights) for the various land cover types and with a good geographical coverage.

The comparison of deforestation effects in observations and climate models is even more challenging. First, the respective variables in the models are only a proxy of the variables that were recorded in observation-based data-sets (see ~~Methods~~ Sect. 2.2 for the MPI-ESM). Second, model-based studies usually analyzed the combination of local and nonlocal effects (especially relevant for simulations of large-scale deforestation where the nonlocal effects can be large), while observation-based studies only analyzed local effects, for which T_{surf} and T_{2m} respond differently (Fig. 4). Any nonlocal effects are excluded from the observations because possible nonlocal effects are present both in forest locations and nearby open land, and thus the nonlocal effects cancel out when looking at the difference between forests and open land, which is acknowledged by these studies (e.g., Li et al., 2015; Alkama and Cescatti, 2016; Bright et al., 2017; Duveiller et al., 2018). Note that Earth system models consider further climate effects when simulating deforestation-induced releases of land carbon into the atmosphere (e.g., Pongratz et al., 2010; Le Quéré et al., 2017). Because CO_2 is a well-mixed greenhouse gas the resulting warming can be expected to act essentially nonlocally and likely influences ~~influence~~ surface and air temperature similarly.

The different ~~temperature variables that are considered in studies about the deforestation effects are relevant for different questions and applications. Satellite-based studies on changes in radiometric surface temperature provided important information about the biophysical mechanisms of surface energy partitioning and thereby surface-atmosphere interactions (Duveiller et al., 2018), as well as habitat and vegetative function (De Frenne et al., 2013). Compared to changes in surface temperature, changes in air temperature may be considered more relevant for human living conditions because it matters for the perceived temperature (e.g., Staiger et al., 2011). Within- and below-canopy air temperature is the most relevant variable for organisms that live within the forests (e.g., De Frenne et al., 2013). However, there are little observations and few models can simulate vertical within-canopy temperature profiles (e.g., Chen et al., 2016). Hence, we did not address within-canopy temperature in the current study.~~

~~The different~~ response of surface temperature (T_{surf}) and air temperature (T_{2m}) is relevant for climate policies. Strategies that aim at adapting locally to warming air temperature may focus on perceived temperature and thus T_{2m}, but this study shows that the local effects on T_{2m} may substantially differ from those on T_{surf}~~, in particular~~. Our results for the MPI-ESM suggest that the difference between T_{2m} and T_{surf} is particularly strong for mean daily maximum temperature (see Fig. 2). Further studies may investigate whether this is also true for other climate models and observation-based data-sets. Consequently, strategies in the agricultural sector that aim at adapting locally to warming soil and canopy temperatures may focus on the local effects on surface temperature because this variable is relevant for the organisms that live there. On the other hand, for international policies that aim at mitigating global warming, what matters is not only temperature at the location of deforestation but also in nearby and in remote regions. Thus, international policies ~~mainly~~ may additionally consider the nonlocal effects. For the nonlocal effects, the response of T_{surf} and T_{2m} are rather similar (Fig. 4) and a distinction between the two temperature measures is therefore less relevant. To sum up, this study emphasizes that the local biogeophysical effects of deforestation influence T_{surf} and T_{2m} differently, and thus, a careful choice based on the respective application has to be made whether a study should focus on changes in surface temperature or near-surface air temperature.

Author contributions. J.W., C.H.R and J.P. designed the research; J.W. performed the simulations with the MPI-ESM, analyzed the data and drafted the manuscript. All authors contributed to the interpretation of the data and revision of the manuscript.

Competing interests. The authors declare no competing financial interests.

Acknowledgements. Our simulations were performed at the German Climate Computing Center (DKRZ). This work was supported by the German Research Foundation's Emmy Noether Program (PO 1751). PCS acknowledges the U.S. National Science Foundation awards DEB-1552976, and EF-1702029. We want to thank all groups who provided data for the inter-model comparison, and Vivek Arora discussions on the results for the CanESM2. Primary data and scripts used in the analysis and other supporting information that may be useful in reproducing the author's work are archived by the Max Planck Institute for Meteorology and can be obtained by contacting publications@mpimet.mpg.de.

~~Alkama, R. and Cescatti, A. (2016). Biophysical climate impacts of recent changes in global forest cover. Science, 351:600–604.~~

~~Bala, G., Caldeira, K., Wickett, M., Phillips, T. J., Lobell, D. B., Delire, C., and Mirin, A. (2007). Combined climate and carbon-cycle effects of large-scale deforestation. Proceedings of the National Academy of Sciences, 104(16):6550–6555.~~

~~Bathiany, S., Claussen, M., Brovkin, V., Raddatz, T., and Gayler, V. (2010). Combined biogeophysical and biogeochemical effects of large-scale forest cover changes in the MPI Earth system model. Biogeosciences, 7:1383–1399.~~

~~Boisier, J. P., de Noblet-Ducoudré, N., Pitman, a. J., Cruz, F. T., Delire, C., van den Hurk, B. J. J. M., van der Molen, M. K., Müller, C., and Voldoire, A. (2012). Attributing the impacts of land-cover changes in temperate regions on surface temperature and heat fluxes to specific causes: Results from the first LUCID set of simulations. Journal of Geophysical Research: Atmospheres, 117:1–16.~~

~~Bonan, G. B. (2008). Forests and climate change: forcings, feedbacks, and the climate benefits of forests.Science, 320:1444–1449.~~

~~Bright, R. M., Davin, E. L., O'Halloran, T. L., Pongratz, J., Zhao, K., and Cescatti, A. (2017). Local temperature response to land cover and management change driven by non-radiative processes. Nature Climate Change, 7:296–302.~~

~~Campbell, G. S. and Norman, J. M. (1998). An Introduction to Environmental Biophysics. Springer-Verlag New York.~~

~~Chen, J., Saunders, S. C., Crow, T. R., Naiman, R. J., Brosofske, K. D., Mroz, G. D., Brookshire, B. L., and Franklin, J. F. (1999). Microclimate in Forest Ecosystem and Landscape Ecology. BioScience, 49(4):288–297.~~

~~Chen, Y., Ryder, J., Bastrikov, V., McGrath, M. J., Naudts, K., Otto, J., Ottlé, C., Peylin, P., Polcher, J., Valade, A., Black, A., Elbers, J. A., Moors, E., Foken, T., Van Gorsel, E., Haverd, V., Heinesch, B., Tiedemann, F., Knohl, A., Launiainen, S., Loustau, D., Ogeé, J., Vessala, T., and Luyssaert, S. (2016). Evaluating the performance of land surface model ORCHIDEE-CAN v1.0 on water and energy flux estimation with a single-and multi-layer energy budget scheme. Geoscientific Model Development, 9(9):2951–2972.~~

~~Claussen, M., Brovkin, V., and Ganopolski, A. (2001). Biogeophysical versus biogeochemical feedbacks of large-scale land cover change. Geophysical Research Letters, 28:1011–1014.~~

~~Davin, E. L. and de Noblet-Ducoudre, N. (2010). Climatic impact of global-scale Deforestation: Radiative versus nonradiative processes. Journal of Climate, 23(1):97–112.~~

~~De Frenne, P., Rodriguez-Sanchez, F., Coomes, D. A., Baeten, L., Verstraeten, G., Vellend, M., Bernhardt-Romermann, M., Brown, C. D., Brunet, J., Cornelis, J., Decocq, G. M., Dierschke, H., Eriksson, O., Gilliam, F. S., Hedl, R., Heinken, T., Hermy, M., Hommel, P., Jenkins, M. A., Kelly, D. L., Kirby, K. J., Mitchell, F. J. G., Naaf, T., Newman, M., Peterken, G., Petrik, P., Schultz, J., Sonnier, G., Van Calster, H., Waller, D. M., Walther, G.-R., White, P. S., Woods, K. D., Wulf, M., Graae, B. J., and Verheyen, K. (2013). Microclimate moderates plant responses to macroclimate warming. Proceedings of the National Academy of Sciences, 110(46):18561–18565.~~

~~de Noblet-Ducoudré, N., Boisier, J.-P., Pitman, A., Bonan, G. B., Brovkin, V., Cruz, F., Delire, C., Gayler, V., van den Hurk, B. J. J. M., Lawrence, P. J., van der Molen, M. K., Müller, C., Reick, C. H., Strengers, B. J., and Voldoire, A. (2012). Determining robust impacts of land-use-induced land cover changes on surface climate over North America and Eurasia: Results from the first set of LUCID experiments. Journal of Climate, 25:3261–3281.~~

~~Deser, C., Knutti, R., Solomon, S., and Phillips, A. S. (2012). Communication of the role of natural variability in future North American climate. Nature Climate Change, 2:775–779.~~

~~Devaraju, N., Bala, G., and Modak, A. (2015). Effects of large-scale deforestation on precipitation in the monsoon regions: Remote versus local effects. Proceedings of the National Academy of Sciences, 112:3257–3262.~~

~~Duveiller, G., Hooker, J., and Cescatti, A. (2018). The mark of vegetation change on Earth's surface energy balance. Nature Communications, 9(1):1–12.~~

~~ECMWF Research Department(1991). Research Manual 3, ECMWF forecast model, Physical parametrization, 3rd Edition.~~

~~Findell, K. L., Knutson, T. R., and Milly, P. C. D. (2006). Weak simulated extratropical responses to complete tropical deforestation. Journal of Climate, 19:2835–2850.~~

~~Gibbard, S., Caldeira, K., Bala, G., Phillips, T. J., and Wickett, M. (2005). Climate effects of global land cover change. Geophysical Research Letters, 32:1–4.~~

~~Giorgetta, M. A., Roeckner, E., Mauritsen, T., Bader, J., Crueger, T., Esch, M., Rast, S., Kornblueh, L., Schmidt, H., Kinne, S., Hohenegger, C., Möbis, B., Krismer, T., Wieners, K.-H., and Stevens, B. (2013). The atmospheric general circulation model ECHAM6 - Model description. Technical Report 135, Max-Planck-Institute for Meteorology, Hamburg.~~

~~Hansen, M. C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S. a., and Tyukavina, A. (2013). High-resolution global maps of 21st-century forest cover change. Science, 342:850–853.~~

~~Hou, P., Chen, Y., Qiao, W., Cao, G., Jiang, W., and Li, J. (2013). Near-surface air temperature retrieval from satellite images and influence by wetlands in urban region. Theoretical and Applied Climatology, 111(1-2):109–118.~~

~~Jin, M. and Dickinson, R. E. (2010). Land surface skin temperature climatology: Benefitting from the strengths of satellite observations. Environmental Research Letters, 5(4).~~

~~Jones, A. D., Collins, W. D., and Torn, M. S. (2013). On the additivity of radiative forcing between land use change and greenhouse gases. Geophysical Research Letters, 40(15):4036–4041.~~

~~Lague, M. and Swann, A. (2016). Progressive Midlatitude Afforestation: Impacts on Clouds, Global Energy Transport, and Precipitation. Journal of Climate, 29:5561–5573.~~

~~Le Quéré, C., Andrew, R. M., Friedlingstein, P., Sitch, S., Pongratz, J., Manning, A. C., Korsbakken, J. I., Peters, G. P., Canadell, J. G., Jackson, R. B., Boden, T. A., Tans, P. P., Andrews, O. D., Arora, V. K., Bakker, D. C. E., Barbero, L., Becker, M., Betts, R. A., Bopp, L., Chevallier, F., Chini, L. P., Ciais, P., Cosca, C. E., Cross, J., Currie, K., Gasser, T., Harris, I., Hauck, J., Haverd, V., Houghton, R. A., Hunt, C. W., Hurtt, G., Ilyina, T., Jain, A. K., Kato, E., Kautz, M., Keeling, R. F., Klein Goldewijk, K., Körtzinger, A., Landschützer, P., Lefèvre, N., Lenton, A., Lienert, S., Lima, I., Lombardozzi, D., Metzl, N., Millero, F., Monteiro, P. M. S., Munro, D. R., Nabel, J. E. M. S., Nakaoka, S.-i., Nojiri, Y., Padín, X. A., Peregon, A., Pfeil, B., Pierrot, D., Poulter, B., Rehder, G., Reimer, J., Rödenbeck, C., Schwinger, J., Séférian, R., Skjelvan, I., Stocker, B. D., Tian, H., Tilbrook, B., van der Laan-Luijkx, I. T., van der Werf, G. R., van Heuven, S., Viovy, N., Vuichard, N., Walker, A. P., Watson, A. J., Wiltshire, A. J., Zaehle, S., and Zhu, D. (2017). Global Carbon Budget 2017. Earth System Science Data Discussions, pages 1–79.~~

~~Leclerc, M. and Foken, T. (2014). Footprints in Micrometeorology and Ecology. Springer Berlin Heidelberg.~~

~~Lee, X., Goulden, M. L., Hollinger, D. Y., Barr, A., Black, T. A., Bohrer, G., Bracho, R., Drake, B., Goldstein, A., Gu, L., Katul, G., Kolb, T., Law, B. E., Margolis, H., Meyers, T., Monson, R., Munger, W., Oren, R., Paw U, K. T., Richardson, A. D., Schmid, H. P., Staebler, R., Wofsy, S., and Zhao, L. (2011). Observed increase in local cooling effect of deforestation at higher latitudes. Nature, 479:384–387.~~

~~Lejeune, Q., Davin, E. L., Gudmundsson, L., Winckler, J., and Seneviratne, S. I. (2018). Historical deforestation increased the risk of heat extremes in northern mid-latitudes. Nature Climate Change, 8:386–390.~~

~~Lejeune, Q., Seneviratne, S. I., and Davin, E. L. (2017). Historical land-cover change impacts on climate: Comparative assessment of LUCID and CMIP5 multimodel experiments. Journal of Climate, 30:1439–1459.~~

~~Li, Y., de Noblet-Ducoudré, N., Davin, E. L., Zeng, N., Motesharrei, S., Li, S. C., and Kalnay, E. (2016). The role of spatial scale and background climate in the latitudinal temperature response to deforestation. Earth System Dynamics Discussions, 7:167–181.~~

~~Li, Y., Zhao, M., Motesharrei, S., Mu, Q., Kalnay, E., and Li, S. (2015). Local cooling and warming effects of forests based on satellite observations.Nature Communications, 6:1–8.~~

~~Luyssaert, S., Schulze, E.-D., Börner, A., Knohl, A., Hessenmöller, D., Law, B. E., Ciais, P., and Grace, J. (2008). Old-growth forests as global carbon sinks.Nature, 455(7210):213–215.~~

~~Pitman, A. J., de Noblet-Ducoudré, N., Cruz, F. T., Davin, E. L., Bonan, G. B., Brovkin, V., Claussen, M., Delire, C., Ganzeveld, L., Gayler, V., van den Hurk, B. J. J. M., Lawrence, P. J., van der Molen, M. K., Müller, C., Reick, C. H., Seneviratne, S. I., Strengers, B. J., and Voldoire, A. (2009). Uncertainties in climate responses to past land cover change: First results from the LUCID intercomparison study. Geophysical Research Letters, 36:1–6.~~

~~Pongratz, J., Reick, C. H., Raddatz, T., and Claussen, M. (2008). A reconstruction of global agricultural areas and land cover for the last millennium. Global Biogeochemical Cycles, 22:1–16.~~

~~Pongratz, J., Reick, C. H., Raddatz, T., and Claussen, M. (2010). Biogeophysical versus biogeochemical climate response to historical anthropogenic land cover change. Geophys. Res. Lett., 37:1–5.~~

~~Ramankutty, N. and Foley, J. A. (1999). Estimating historical changes in global land cover: Croplands from 1700 to 1992. Global Biogeochemical Cycles, 13(4):997–1027.~~

~~Schultz, N. M., Lawrence, P. J., and Lee, X. (2017). Global satellite data highlights the diurnal asymmetry of the surface temperature response to deforestation. Journal of Geophysical Research: Biogeosciences, 122(4):903–917.~~

~~Staiger, H., Laschewski, G., and Graetz, A. (2011). The perceived temperature – a versatile index for the assessment of the human thermal environment. Part A: Scientific basics. International Journal of Biometeorology, 56:165–176.~~

~~Stevens, B., Giorgetta, M., Esch, M., Mauritsen, T., Crueger, T., Rast, S., Salzmann, M., Schmidt, H., Bader, J., Block, K., Brokopf, R., Fast, I., Kinne, S., Kornblueh, L., Lohmann, U., Pincus, R., Reichler, T., and Roeckner, E. (2013). Atmospheric component of the MPI-M earth system model: ECHAM6. Journal of Advances in Modeling Earth Systems, 5(2):146–172.~~

~~Swann, A. L. S., Fung, I. Y., and Chiang, J. C. H. (2012). Mid-latitude afforestation shifts general circulation and tropical precipitation. Proceedings of the National Academy of Sciences, 109:712–716.~~

~~Taylor, K. E., Stouffer, R. J., and Meehl, G. A. (2012). An Overview of CMIP5 and the Experiment Design. Bulletin of the American Meteorological Society, pages 485–498.~~

~~UNFCCC (2011). The Cancun Agreements: Land use, land-use change and forestry in Report of the Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol on its sixth session. pages 1–32.~~

~~Vanden Broucke, S., Luyssaert, S., Davin, E. L., Janssens, I., Lipzig, N., Broucke, S. V., Luyssaert, S., Davin, E. L., Janssens, I., and Lipzig, N. (2015). New insights in the capability of climate models to simulate the impact of LUC based on temperature decomposition of paired site observations. Journal of Geophysical Research: Atmospheres, 120(11):1–20.~~

~~Von Engeln, A. and Bühler, S. (2002). Temperature profile determination from microwave oxygen emissions in limb sounding geometry. Journal of Geophysical Research Atmospheres, 107(19):1–15.~~

~~Winckler, J., Reick, C. H., Lejeune, Q., and Pongratz, J. (2018). Nonlocal effects dominate the global mean surface temperature response to the biogeophysical effects of deforestation (submitted). .~~

~~Winckler, J., Reick, C. H., and Pongratz, J. (2017). Robust identification of local biogeophysical effects of land-cover change in a global climate model. Journal of Climate, 30(3):1159–1176.~~

~~WMO (2008). Guide to Meteorological Instruments and Methods of observation, volume I &II.~~

~~Zhang, M., Lee, X., Yu, G., Han, S., Wang, H., Yan, J., Zhang, Y., Li, Y., Ohta, T., Hirano, T., Kim, J., Yoshifuji, N., and Wang, W. (2014). Response of surface air temperature to small-scale land clearing across latitudes. Environmental Research Letters, 9(034002):7.~~

References

Alkama, R. and Cescatti, A.: Biophysical climate impacts of recent changes in global forest cover, Science, 351, 600–604, https://doi.org/10.1126/science.aac8083, 2016.

Bala, G., Caldeira, K., Wickett, M., Phillips, T. J., Lobell, D. B., Delire, C., and Mirin, A.: Combined climate and carbon-cycle effects of large-scale deforestation, Proceedings of the National Academy of Sciences, 104, 6550–6555, https://doi.org/10.1073/pnas.0608998104, 2007.

Baldocchi, D.: How will land use affect air temperature in the surface boundary layer? Lessons learned from a comparative study on the energy balance of an oak savanna and annual grassland in California, USA, Tellus B, https://doi.org/10.3402/tellusb.v65i0.19994, 2013.

Bathiany, S., Claussen, M., Brovkin, V., Raddatz, T., and Gayler, V.: Combined biogeophysical and biogeochemical effects of large-scale forest cover changes in the MPI Earth system model, Biogeosciences, 7, 1383–1399, https://doi.org/10.5194/bg-7-1383-2010, 2010.

Boisier, J. P., de Noblet-Ducoudré, N., Pitman, A. J., Cruz, F. T., Delire, C., van den Hurk, B. J. J. M., van der Molen, M. K., Müller, C., and Voldoire, A.: Attributing the impacts of land-cover changes in temperate regions on surface temperature and heat fluxes to specific causes: Results from the first LUCID set of simulations, Journal of Geophysical Research: Atmospheres, 117, 1–16, https://doi.org/10.1029/2011JD017106, 2012.

Bonan, G. B.: Forests and climate change: forcings, feedbacks, and the climate benefits of forests., Science, 320, 1444–1449, https://doi.org/10.1126/science.1155121, 2008.

Bright, R. M., Davin, E. L., O'Halloran, T. L., Pongratz, J., Zhao, K., and Cescatti, A.: Local temperature response to land cover and management change driven by non-radiative processes, Nature Climate Change, 7, 296–302, https://doi.org/10.1038/nclimate3250, 2017.

Campbell, G. S. and Norman, J. M.: An Introduction to Environmental Biophysics, Springer-Verlag New York, https://doi.org/10.1007/978-1-4612-1626-1, 1998.

Chen, J., Saunders, S. C., Crow, T. R., Naiman, R. J., Brosofske, K. D., Mroz, G. D., Brookshire, B. L., and Franklin, J. F.: Microclimate in Forest Ecosystem and Landscape Ecology, BioScience, 49, 288–297, 1999.

Chen, Y., Ryder, J., Bastrikov, V., McGrath, M. J., Naudts, K., Otto, J., Ottlé, C., Peylin, P., Polcher, J., Valade, A., Black, A., Elbers, J. A., Moors, E., Foken, T., Van Gorsel, E., Haverd, V., Heinesch, B., Tiedemann, F., Knohl, A., Launiainen, S., Loustau, D., Ogeé, J., Vessala, T., and Luyssaert, S.: Evaluating the performance of land surface model ORCHIDEE-CAN v1.0 on water and energy flux estimation with a single-and multi-layer energy budget scheme, Geoscientific Model Development, 9, 2951–2972, https://doi.org/10.5194/gmd-9-2951-2016, 2016.

Claussen, M., Brovkin, V., and Ganopolski, A.: Biogeophysical versus biogeochemical feedbacks of large-scale land cover change, Geophysical Research Letters, 28, 1011–1014, 2001.

Davin, E. L. and de Noblet-Ducoudre, N.: Climatic impact of global-scale deforestation: radiative versus nonradiative processes, Journal of Climate, 23, 97–112, https://doi.org/10.1175/2009JCLI3102.1, 2010.

De Frenne, P., Rodriguez-Sanchez, F., Coomes, D. A., Baeten, L., Verstraeten, G., Vellend, M., Bernhardt-Romermann, M., Brown, C. D., Brunet, J., Cornelis, J., Decocq, G. M., Dierschke, H., Eriksson, O., Gilliam, F. S., Hedl, R., Heinken, T., Hermy, M., Hommel, P., Jenkins, M. A., Kelly, D. L., Kirby, K. J., Mitchell, F. J. G., Naaf, T., Newman, M., Peterken, G., Petrik, P., Schultz, J., Sonnier, G., Van Calster, H., Waller, D. M., Walther, G.-R., White, P. S., Woods, K. D., Wulf, M., Graae, B. J., and Verheyen, K.: Microclimate moderates plant responses to macroclimate warming, Proceedings of the National Academy of Sciences, 110, 18 561–18 565, https://doi.org/10.1073/pnas.1311190110, 2013.

de Noblet-Ducoudré, N., Boisier, J.-P., Pitman, A., Bonan, G. B., Brovkin, V., Cruz, F., Delire, C., Gayler, V., van den Hurk, B. J. J. M., Lawrence, P. J., van der Molen, M. K., Müller, C., Reick, C. H., Strengers, B. J., and Voldoire, A.: Determining robust impacts of land-use-induced land cover changes on surface climate over North America and Eurasia: Results from the first set of LUCID experiments, Journal of Climate, 25, 3261–3281, https://doi.org/10.1175/JCLI-D-11-00338.1, 2012.

Deser, C., Knutti, R., Solomon, S., and Phillips, A. S.: Communication of the role of natural variability in future North American climate, Nature Climate Change, 2, 775–779, https://doi.org/10.1038/nclimate1562, 2012.

Devaraju, N., Bala, G., and Modak, A.: Effects of large-scale deforestation on precipitation in the monsoon regions: Remote versus local effects, Proceedings of the National Academy of Sciences, 112, 3257–3262, https://doi.org/10.1073/pnas.1423439112, 2015.

Duveiller, G., Hooker, J., and Cescatti, A.: The mark of vegetation change on Earth's surface energy balance, Nature Communications, 9, 1–12, https://doi.org/10.1038/s41467-017-02810-8, 2018.

ECMWF Research Department: Research Manual 3, ECMWF forecast model, Physical parametrization, 3rd Edition, 1991.

Findell, K. L., Knutson, T. R., and Milly, P. C. D.: Weak simulated extratropical responses to complete tropical deforestation, Journal of Climate, 19, 2835–2850, https://doi.org/10.1175/JCLI3737.1, 2006.

Gibbard, S., Caldeira, K., Bala, G., Phillips, T. J., and Wickett, M.: Climate effects of global land cover change, Geophysical Research Letters, 32, 1–4, https://doi.org/10.1029/2005GL024550, 2005.

Giorgetta, M. A., Roeckner, E., Mauritsen, T., Bader, J., Crueger, T., Esch, M., Rast, S., Kornblueh, L., Schmidt, H., Kinne, S., Hohenegger, C., Möbis, B., Krismer, T., Wieners, K.-H., and Stevens, B.: The atmospheric general circulation model ECHAM6 - Model description, Tech. Rep. 135, Max-Planck-Institute for Meteorology, Hamburg, 2013.

Hansen, M. C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S. a., and Tyukavina, A.: High-resolution global maps of 21st-century forest cover change, Science, 342, 850–853, https://doi.org/10.1126/science.1244693, 2013.

Hou, P., Chen, Y., Qiao, W., Cao, G., Jiang, W., and Li, J.: Near-surface air temperature retrieval from satellite images and influence by wetlands in urban region, Theoretical and Applied Climatology, 111, 109–118, https://doi.org/10.1007/s00704-012-0629-7, 2013.

Jin, M. and Dickinson, R. E.: Land surface skin temperature climatology: Benefitting from the strengths of satellite observations, Environmental Research Letters, 5, https://doi.org/10.1088/1748-9326/5/4/044004, 2010.

Jones, A. D., Collins, W. D., and Torn, M. S.: On the additivity of radiative forcing between land use change and greenhouse gases, Geophysical Research Letters, 40, 4036–4041, https://doi.org/10.1002/grl.50754, 2013.

Lague, M. and Swann, A.: Progressive Midlatitude Afforestation: Impacts on Clouds, Global Energy Transport, and Precipitation, Journal of Climate, 29, 5561–5573, https://doi.org/10.1175/JCLI-D-15-0748.1, 2016.

Le Quéré, C., Andrew, R. M., Canadell, J. G., Sitch, S., Ivar Korsbakken, J., Peters, G. P., Manning, A. C., Boden, T. A., Tans, P. P., Houghton, R. A., Keeling, R. F., Alin, S., Andrews, O. D., Anthoni, P., Barbero, L., Bopp, L., Chevallier, F., Chini, L. P., Ciais, P., Currie, K., Delire, C., Doney, S. C., Friedlingstein, P., Gkritzalis, T., Harris, I., Hauck, J., Haverd, V., Hoppema, M., Klein Goldewijk, K., Jain, A. K., Kato, E., Körtzinger, A., Landschützer, P., Lefèvre, N., Lenton, A., Lienert, S., Lombardozzi, D., Melton, J. R., Metzl, N., Millero, F., Monteiro, P. M., Munro, D. R., Nabel, J. E., Nakaoka, S. I., O'Brien, K., Olsen, A., Omar, A. M., Ono, T., Pierrot, D., Poulter, B., Rödenbeck, C., Salisbury, J., Schuster, U., Schwinger, J., Séférian, R., Skjelvan, I., Stocker, B. D., Sutton, A. J., Takahashi, T., Tian, H., Tilbrook, B., Van Der Laan-Luijkx, I. T., Van Der Werf, G. R., Viovy, N., Walker, A. P., Wiltshire, A. J., and Zaehle, S.: Global carbon budget 2016, Earth System Science Data, 8, 605–649, https://doi.org/10.5194/essd-8-605-2016, 2017.

Leclerc, M. and Foken, T.: Footprints in Micrometeorology and Ecology, Springer Berlin Heidelberg, https://doi.org/10.1007/978-3-642-54545-0, 2014.

Lee, X., Goulden, M. L., Hollinger, D. Y., Barr, A., Black, T. A., Bohrer, G., Bracho, R., Drake, B., Goldstein, A., Gu, L., Katul, G., Kolb, T., Law, B. E., Margolis, H., Meyers, T., Monson, R., Munger, W., Oren, R., Paw U, K. T., Richardson, A. D., Schmid, H. P., Staebler, R., Wofsy, S., and Zhao, L.: Observed increase in local cooling effect of deforestation at higher latitudes, Nature, 479, 384–387, https://doi.org/10.1038/nature10588, 2011.

Lejeune, Q., Seneviratne, S. I., and Davin, E. L.: Historical land-cover change impacts on climate: Comparative assessment of LUCID and CMIP5 multimodel experiments, Journal of Climate, 30, 1439–1459, https://doi.org/10.1175/JCLI-D-16-0213.1, 2017.

Lejeune, Q., Davin, E. L., Gudmundsson, L., Winckler, J., and Seneviratne, S. I.: Historical deforestation increased the risk of heat extremes in northern mid-latitudes, Nature Climate Change, 8, 386–390, https://doi.org/10.1038/s41558-018-0131-z, 2018.

Li, Y., Zhao, M., Motesharrei, S., Mu, Q., Kalnay, E., and Li, S.: Local cooling and warming effects of forests based on satellite observations., Nature Communications, 6, 1–8, https://doi.org/10.1038/ncomms7603, 2015.

Li, Y., de Noblet-Ducoudré, N., Davin, E. L., Zeng, N., Motesharrei, S., Li, S. C., and Kalnay, E.: The role of spatial scale and background climate in the latitudinal temperature response to deforestation, Earth System Dynamics Discussions, 7, 167–181, https://doi.org/10.5194/esdd-6-1897-2015, 2016.

Luyssaert, S., Schulze, E.-D., Börner, A., Knohl, A., Hessenmöller, D., Law, B. E., Ciais, P., and Grace, J.: Old-growth forests as global carbon sinks., Nature, 455, 213–215, https://doi.org/10.1038/nature07276, 2008.

Luyssaert, S., Marie, G., Valade, A., Chen, Y.-y., Djomo, S. N., Ryder, J., Otto, J., Naudts, K., Lansø, A. S., Ghattas, J., and Mcgrath, M. J.: Trade-offs in using European forests to meet climate objectives, Nature, 562, 259–262, https://doi.org/10.1038/s41586-018-0577-1, 2018.

Malyshev, S., Shevliakova, E., Stouffer, R. J., and Pacala, S. W.: Contrasting local versus regional effects of land-use-change-induced heterogeneity on historical climate: Analysis with the GFDL Earth system model, Journal of Climate, 28, 5448–5469, https://doi.org/10.1175/JCLI-D-14-00586.1, 2015.

Meier, R., Davin, E. L., Lejeune, Q., Hauser, M., Li, Y., Martens, B., Schultz, N. M., Sterling, S., and Thiery, W.: Evaluating and improving the Community Land Model's sensitivity to land cover, Biogeosciences, 15, 4731–4757, 2018.

Melo-Aguilar, C., Gonzalez-Rouco, J. F., Garcia-Bustamante, E., Navarro-Montesinos, J., and Steinert, N.: Influence of radiative forcing factors on ground–air temperature coupling during the last millennium: implications for borehole climatology, Climate of the Past, 14, 1583–1606, 2018.

Pitman, A. J., de Noblet-Ducoudré, N., Cruz, F. T., Davin, E. L., Bonan, G. B., Brovkin, V., Claussen, M., Delire, C., Ganzeveld, L., Gayler, V., van den Hurk, B. J. J. M., Lawrence, P. J., van der Molen, M. K., Müller, C., Reick, C. H., Seneviratne, S. I., Strengers, B. J., and Voldoire, A.: Uncertainties in climate responses to past land cover change: First results from the LUCID intercomparison study, Geophysical Research Letters, 36, 1–6, https://doi.org/10.1029/2009GL039076, 2009.

Pongratz, J., Reick, C. H., Raddatz, T., and Claussen, M.: A reconstruction of global agricultural areas and land cover for the last millennium, Global Biogeochemical Cycles, 22, 1–16, https://doi.org/10.1029/2007GB003153, 2008.

Pongratz, J., Reick, C. H., Raddatz, T., and Claussen, M.: Biogeophysical versus biogeochemical climate response to historical anthropogenic land cover change, Geophys. Res. Lett., 37, 1–5, https://doi.org/10.1029/2010GL043010, 2010.

Ramankutty, N. and Foley, J. A.: Estimating historical changes in global land cover: Croplands from 1700 to 1992, Global Biogeochemical Cycles, 13, 997–1027, 1999.

Schultz, N. M., Lawrence, P. J., and Lee, X.: Global satellite data highlights the diurnal asymmetry of the surface temperature response to deforestation, Journal of Geophysical Research: Biogeosciences, 122, 903–917, https://doi.org/10.1002/2016JG003653, 2017.

Staiger, H., Laschewski, G., and Graetz, A.: The perceived temperature – a versatile index for the assessment of the human thermal environment. Part A: Scientific basics, International Journal of Biometeorology, 56, 165–176, https://doi.org/10.1007/s00484-011-0409-6, 2011.

Stevens, B., Giorgetta, M., Esch, M., Mauritsen, T., Crueger, T., Rast, S., Salzmann, M., Schmidt, H., Bader, J., Block, K., Brokopf, R., Fast, I., Kinne, S., Kornblueh, L., Lohmann, U., Pincus, R., Reichler, T., and Roeckner, E.: Atmospheric component of the MPI-M Earth System Model: ECHAM6, Journal of Advances in Modeling Earth Systems, 5, 146–172, https://doi.org/10.1002/jame.20015, 2013.

Swann, A. L. S., Fung, I. Y., and Chiang, J. C. H.: Mid-latitude afforestation shifts general circulation and tropical precipitation, Proceedings of the National Academy of Sciences, 109, 712–716, https://doi.org/10.1073/pnas.1116706108, 2012.

Taylor, K. E., Stouffer, R. J., and Meehl, G. A.: An Overview of CMIP5 and the Experiment Design, Bulletin of the American Meteorological Society, pp. 485–498, https://doi.org/10.1175/BAMS-D-11-00094.1, 2012.

UNFCCC: The Cancun Agreements: Land use, land-use change and forestry in Report of the Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol on its sixth session, pp. 1–32, 2011.

Vanden Broucke, S., Luyssaert, S., Davin, E. L., Janssens, I., Lipzig, N., Broucke, S. V., Luyssaert, S., Davin, E. L., Janssens, I., and Lipzig, N.: New insights in the capability of climate models to simulate the impact of LUC based on temperature decomposition of paired site observations, Journal of Geophysical Research: Atmospheres, 120, 1–20, https://doi.org/10.1002/2015JD023095, 2015.

Von Engeln, A. and Bühler, S.: Temperature profile determination from microwave oxygen emissions in limb sounding geometry, Journal of Geophysical Research Atmospheres, 107, 1–15, https://doi.org/10.1029/2001JD001029, 2002.

Winckler, J., Reick, C. H., and Pongratz, J.: Robust identification of local biogeophysical effects of land-cover change in a global climate model, Journal of Climate, 30, 1159–1176, https://doi.org/10.1175/JCLI-D-16-0067.1, 2017.

Winckler, J., Reick, C. H., Lejeune, Q., and Pongratz, J.: Nonlocal effects dominate the global mean surface temperature response to the biogeophysical effects of deforestation, Geophysical Research Letters, https://doi.org/doi: 10.1029/2018gl080211, 2018.

WMO: Guide to Meteorological Instruments and Methods of observation, vol. I & II, 2008.

Zhang, M., Lee, X., Yu, G., Han, S., Wang, H., Yan, J., Zhang, Y., Li, Y., Ohta, T., Hirano, T., Kim, J., Yoshifuji, N., and Wang, W.: Response of surface air temperature to small-scale land clearing across latitudes, Environmental Research Letters, 9, 7, https://doi.org/10.1088/1748-9326/9/3/034002, 2014.

Zwiers, F. W. and von Storch, H.: Taking serial correlation into account in tests of the mean, Journal of Climate, 8, 336–351, https://doi.org/10.1175/1520-0442(1995)008<0336:TSCIAI>2.0.CO;2, 1995.