This file contains our point-to-point response to review comments (Part 1) and our revised manuscript with tracked-changes (Part 2).

**Part 1: Response to reviewer’s comments**

We deeply thank the two reviewers for their time and helpful, important comments. Below is our point-to-point response to each comment. The original comments are in bold, our responses are in regular font and relevant changes in text are in italic font.

**Anonymous Referee #1**

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Dear Authors,

I congratulate you to this paper which elegantly addresses many aspects of deforestation-induced climate change such as local versus remote effects of deforestation, the nonlinear dependence of the magnitude of change on the scale of deforestation, a decomposition of the total change into contributions from the three most important biophysical factors, and an explanation of the latitudinal change signal in terms of background climate conditions. I only have some minor suggestions, questions and technical corrections.

Thanks for your favorable comments.

p1899l20–23 “Further analysis [. . . :]”: I do not really understand this sentence. Surely, it can be written more intelligibly.

This sentence has been revised:

“Our analysis reveals that the latitudinal temperature change largely results from the climate conditions in which deforestation occurs, and is less influenced by the magnitude of individual biophysical changes such as albedo, roughness, and evapotranspiration efficiency.”

p1903l3–6 So VEGAS does calculate a land surface albedo. Why don’t you use these data directly? Are the albedo changes calculated by VEGAS used as is, I mean, don’t they need to be adjusted (rescaled maybe) to the corresponding satellite observations?

Yes, VEGAS does calculate vegetation albedo (Av), by using a simple empirical formula as a function of LAI:

\[ Av = A_{\text{min}} + (A_{\text{max}} - A_{\text{min}}) \exp (-kL) \]

where \( A_{\text{min}} = 0.1 \) and \( A_{\text{max}} = 0.45 \) are the minimum and maximum albedo, respectively, and \( k = 0.5 \) is the light extinction coefficient. Here is a detailed explanation on this issue provided by (Zeng & Yoon, 2009): “This simple empirical formula is not sufficient at capturing all the possible processes responsible for the observed albedo, many of which are difficult to model mechanistically at present. For instance, bright deserts with high
albedo values often correspond to sand dunes or dry lake beds whose formations are also related to other hydrogeological processes [Knorr and Schnitzler, 2006]. To minimize potential climate drift due to full coupling, only the anomalies $A'_v$ (changes in $A_v$ relative to a control run) are used by the atmospheric radiation module, i.e., the changes in $A_v$ were added onto the observed surface albedo climatology in order to capture the first-order effects due to vegetation change”

$$A = A_{v,bc} + A'_v$$

And the following explanation words has been added to the text:

“Vegetation-albedo feedback is treated in the model by introducing albedo anomalies. This procedure sums the albedo change due to vegetation change (calculated by VEGAS using an empirical formula as a function of leaf area index (LAI)), and the observed albedo climatology used by the atmospheric radiation module (Zeng & Yoon, 2009). This albedo anomalies treatment prioritizes the capture of the first-order effects of albedo change due to vegetation change, since many of the possible processes that are responsible for the observed albedo are difficult to model mechanistically.”

p1903l25–27 Please briefly discuss the limitations this entails. For example, would your results change much if you used a perpetual 30-year (1960–1990) cycle of SST observations? Please also state which SST data you used.

SST data are from HadSST and we have revised the sentence to include this information. “The model is driven by a climatological seasonal cycle of SST derived from HadSST (Rayner et al., 2006), averaged over 1960–1990 to smooth the influence of inter-annual climate variability.”

We also added the following content to discussion regarding to the choice of SST climatology.

“In the simulation, we used the SST climatology of 1960-1990 with seasonal cycle only that can minimize inter-annual variability and therefore amplify the strength of deforestation signal to climate variability in terms of statistical significance. If a different period of the SST climatology had been used, the simulated climate may have been slightly different including differences in vegetation distribution and deforestation impacts. Nevertheless, our results are unlikely to be substantially changed by the choice of SST climatology, because a background climate change as large as that coming from $1 \times CO2$ (280 ppm) increased to $2 \times CO2$ (280 ppm) can only modify the climate impact over certain transitional regions (Pitman et al., 2011).”

p1904l3–5 This part is not well written. Please polish. Also, I think you should include some observational precipitation data for comparison in Fig. S2. I mean, you allude to the possibly detrimental impact of precipitation biases on the quality of simulated PFT distributions but then it appears as if you tried to get away from this issue as quickly as possible. Please address the issue briefly but properly.
The idea of comparing the simulated precipitation with observation data is very needed for many cases but it may not very necessary in our case because there are issues for such comparison.

First, bias in simulated climate is expected for a model with intermediate complexity. Therefore, the bias, if any, is tolerable for our experiment because we mainly focus on the climate response to vegetation change as well as its mechanisms rather than accurately reproducing historical or future climate change. Second, what we designed is an idealized experiment, for example, using preindustrial CO2 and seasonal SST data. Strictly speaking, the simulated climate is not comparable to the observed climate in the real world. Due to these fundamental differences, a direct comparison with observations could be problematic and give little help to the paper.

We added above explanation to the text:

"The vegetation map generally has a reasonable geographical distribution but does not perfectly match modern vegetation of the real world. This is expected because the potential vegetation is derived from an equilibrium state with climate. Therefore, any differences in the simulated climate compared to modern climate or any simulation bias, for example, in precipitation (Figure S2), could influence the vegetation distribution. In addition, some bias in simulated climate is expected for a model with intermediate complexity. Such bias is tolerable in our experiments due to the focus on the climate response to vegetation change and its mechanisms as opposed to an accurate reproduction of historical climate change."

What would happen if you replaced the forest by grass? Wouldn’t that be the more realistic change? Please at least briefly address this point in the discussion section.

Replacing forest by grass or crop is also a common practice for deforestation experiment in the literature. Compared to the forest-to-bare conversion, the conversion to grass/crop often leads to smaller biophysical changes in albedo and roughness, thus it is expected to have similar but smaller impact.

We added a new discussion to the text for this issue.

"An alternative strategy of implementing deforestation experiment is to replace trees with grass (crop). This is considered to be more "realistic" than replacing trees with bare ground (Davin & de Noblet-Ducoudré, 2010). The conversion of trees to grass is expected to induce a similar but less pronounced impact on climate (Gibbard et al., 2005), compared to the conversion of trees to bare ground which would represent the maximum impact of deforestation. Despite this difference, both strategies are frequently used in existing literature to represent deforestation, and they yield consistent findings as the operating mechanisms and feedbacks are the same."

Polish your English here, please.
We revised the text:
“The deforestation impact in the simulation is a very strong signal relative to the small
inter-annual variability, making almost all changes over the land statistically significant.
For this reason, significance levels are not shown on the map.”

p1906l21 Precipitation in W/m²: Please use a more common unit throughout the
manuscript or specify the equivalent of 1 W/m² in a more common unit such as
mm/day at first mention.
Thanks for this suggestion. In the revision, we have changed the unit of precipitation to
mm/day for all relevant texts, tables and figures.

p1908l2 “despite different spatial scales”: I don’t understand. . .
We revised this sentence to:
“Overall, an amplified temperature change in the global deforestation experiment is
expected as it generates a stronger perturbation to the atmosphere, but the latitudinal
temperature response is well preserved despite the spatial extent of deforestation
increases from regional to global level.”

p1908l14–16 Please write this more clearly.
We revise the sentence and provide an additional Figure S6 (using albedo change as a
example) to show the non-linearity of the temperature response to deforestation can either
arise from the response of biophysical land parameters to deforestation or from the
climate response (i.e., temperature response) to biophysical changes.

Relevant changes in text are:
“This nonlinearity can either arise from the response of biophysical land parameters to
deforestation, or from the climate response (i.e., temperature response) to biophysical
changes. We found nonlinearities in both of these aspects (Figure S6).”
Figure S6 (a) Response of albedo change to growing deforestation fraction from 25% to 100% and (b) temperature response to albedo change under different deforestation fractions. Data points in the figure are from Table 3.

p1910l1 "when ∆H is considered": I suggest to refer to Tab. 2 once again, here.
We have taken this suggestion in the revision.

p1911l1 Shouldn't you better specify the albedo changes in percent, just as you do for ET?!
Here we want to demonstrate that a given percentage of change in shortwave radiation and ET can lead to the latitudinal pattern in $\Delta SW$ and $\Delta ET$ as a result of background climate. So we use background incoming shortwave radiation and ET for the calculation, multiplied by the percent of change, expressed by albedo and ET reduction rate respectively. In fact, the absolute albedo change itself denotes shortwave change in percent, which is essentially similar to ET reduction rate.

In this calculation we assume changes in absorbed shortwave radiation at surface are solely induced by albedo change. In this case, changes in absorbed shortwave radiation ($\Delta SW$) are:

$$\Delta SW = (SW1^- - SW1^\uparrow) - (SW0^- - SW0^\uparrow)$$

“0”: before change; “1”: after change
And albedo by definition is given by $alb = SW^\uparrow / SW^-$
Since there is no change in $SW^- by assumption, SW1^- = SW0^-$
Therefore,

$$\Delta SW = SW0^\uparrow - SW1^\uparrow = alb0*SW0^- - alb1*SW1^- = (alb0-alb1)*SW0^-.$$ 

This equation indicates that changes in absorbed shortwave radiation ($\Delta SW$) can be calculated by background SW multiplied by albedo change.

"[. . . ] in the tropical region (Table 4) where its effect on climate can be isolated [. . . ]": This holds everywhere, not just in tropical regions, right? Please rephrase.

Thank you for pointing this issue, the sentence has been revised as:

"Effect of roughness on climate can be isolated by the difference All – noRGH. Roughness change as well as its impact are more pronounced in the tropical region (Table 4)."

I guess you mean that even if deforestation was not associated with roughness change, some parts of the tropics would warm because the reduction in evapotranspiration efficiency would still outweigh the albedo impact in those parts. I don’t know how clear you will find this statement but you should definitely rephrase your version.

Yes, that is exactly what it means. We revised the sentence to explain it more clearly:

"Moreover, Figure 8b also shows the combined effects from albedo and evapotranspiration efficiency since roughness effect is excluded. Thus, the existence of a tropical warming in some regions implies that the reduction in evapotranspiration efficiency remains dominant and outweighs the albedo impact in this situation."

"Lower ET” → okay “and higher sensible heat” → not necessarily as you show in Tab. 2.

The original sentence has been revised as:

"The conversion of forest to bare land favors more turbulence energy to be transferred in the form of sensible heat rather than ET, resulting in higher Bowen ratio.

p1914l22 “perhaps”: You don’t need to be so cautious here, do you; doesn’t Sect. 3.4 strongly support this statement?

This is done as suggested.

Tab. 2 The caption is not entirely precise. I assume the \( \Delta \) values of a column refer to averages over the respective latitudinal band specified in the top row? Are these land surface variables? (These two questions also pertain to Tab. 3.) What exactly are the turbulent flux and the available energy?

Caption of Table 2 has been revised to clarify these issues and turbulent flux and the available energy are explained in the table. Similar changes are also made to Table 3.

Revised caption for Table 2:

“Table 2 Changes in key climate variables from regional and global deforestation experiments. “\( \Delta \)” denotes change relative to the control experiment and value for each climate variable is the area-weighted changes over deforested areas for different latitude zones. The symbol “\( \uparrow \)" denotes upward and “\( \downarrow \)” denotes downward. Units are W/m\(^2\) for energy flux, K for temperature, mm/day for precipitation, and unitless for albedo.”

Revised caption for Table 3:

“Table 3 Changes in key climate variables from global deforestation with different deforestation fractions. “\( \Delta \)" denotes change relative to the control experiment and value for each climate variable is the area-weighted changes over deforested areas for different latitude zones. The symbol “\( \uparrow \)" denotes upward and “\( \downarrow \)” denotes downward. Units are W/m\(^2\) for energy flux, K for temperature, mm/day for precipitation, and unitless for albedo.”

Moreover, I wonder why there is a difference in \( \Delta \)albedo between regional and global deforestation scenario runs. Where does this come from?

Yes, there is slight difference for \( \Delta \)albedo between regional and global deforestation experiment over the same region. This difference is very small indeed, \(-0.01\) or less, see Table below. And we have changed the unit for \( \Delta \)albedo in Table 2 and 3 from percentage to absolute change and redo the rounding.

<table>
<thead>
<tr>
<th>Surface Albedo change</th>
<th>Regional Deforestation</th>
<th>Global deforestation</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical</td>
<td>0.264418</td>
<td>0.276663</td>
<td>-0.0122</td>
</tr>
<tr>
<td>Temperate</td>
<td>0.169792</td>
<td>0.179784</td>
<td>-0.0100</td>
</tr>
<tr>
<td>Boreal</td>
<td>0.217404</td>
<td>0.218868</td>
<td>-0.0015</td>
</tr>
</tbody>
</table>

We are not sure about the exact reason for this difference. We list some possible causes.

1. Rounding error.
2. \( \Delta \)albedo induced by vegetation change is the same between regional and global deforestation experiment before it is passed to atmosphere model for radiation calculation.
There might be some other processes (not surface albedo) that lead to the slight differences in the climate response between regional and global deforestation experiments that can also influence shortwave radiation (e.g., relating to scale extent). Because albedo shown in the table is calculated by $SW^\uparrow/\overline{SW^\uparrow}$, therefore, a tiny difference in $SW^\uparrow$ or $\overline{SW^\uparrow}$ between regional and global deforestation experiment can result in a difference in $\Delta$albedo.

**Fig. 6** Why do you show the solid curves for all four deforestation fractions? If I understand the corresponding part in the text correctly, then the curves are just scaled versions of one and the same curve in all subplots, so it would suffice to show only subplot (d). (Okay, I see that the relative changes of ET and SW differ from fraction to fraction. Well, your choice whether to leave it as is or not.)

Four subplots in Fig. 6 show the calculated $\Delta$SW and $\Delta$ET with different combinations of ET reduction rate and albedo change. We want to retain these four calculated scenarios because they indicate the good correspondence between calculated and simulated $\Delta$SW and $\Delta$ET are not coincidence from a single parameter combination.

We revised caption of Fig 6.

"Figure 6. The latitudinal pattern of $\Delta$SW and $\Delta$ET calculated by multiplying their background climate values with different rates for albedo (red number, from 0.02 in (a) to 0.23 in (d)) and ET changes (blue number, from -15% in (a) to -75% in (d)). In (d), dashed lines are simulated changes from global deforestation for comparison with the calculated changes (solid line)."

**2 Technical corrections**

p1902l18–23 Please explain all the abbreviations in the model names.

Done as suggested.

p1913l2 does → did

Done as suggested.

p1917l7 Could you please give a reference for LUMIP.

We Added the website for LUMIP (https://cmip.ucar.edu/lumip), since there hasn’t been any papers published yet.

Fig. 4a Please append a ↓ to $\Delta$LW in the figure legend.

It has been corrected.

Fig. 5 Where you write (e, f) in the caption I guess you mean (d–f).

It has been corrected.

Fig. S2 Wrong unit, I suppose. Fig. S5 Unit missing.

We changed unit for Fig. S2 to mm/day.

And we added unit (m) into caption for Fig. S5.
Moreover, in all map plots, the grid cells seem to be shifted relative to the coastlines by one or at least half a grid cell (certainly for the longitudes, maybe also for the latitudes). Please fix that.

Thanks for pointing out this latitude shift issue. We replace all spatial figures with this issue solved in the revision (see these figures in the revised manuscript).

Anonymous Referee #2

In this manuscript the authors simulate hypothetical deforestation scenarios with an intermediate complexity Earth system model. The then investigate the resulting temperature changes and the mechanisms that cause these, all with a special focus on the latitudinal dependencies. The authors use fixed SST and CO2 contents from 1960-1990.

Overall I find the paper worthwhile and a nice contribution to climate sciences. I would have preferred a more thorough discussion of the state of the art of this topic, and also a little bit more contrasting of the results to other studies. On the second point: The authors explain convincingly, why they can’t do this, though. I like the idea of disentangling the various contributions to the overall temperature change effect. The manuscript doesn’t provide anything groundbreaking new, but nicely quantifies the basic assumptions given. Also, the model, its shortcomings and how they might affect the outcome are discussed well. I particularly like the analysis done for Fig 5. Overall, I don’t see anything that needs major revising.

There are a few minor gripes, mainly with the form, though. On p1904,l1 a map with potential vegetation is mentioned, but I cannot find it.

Sorry, this figure can be found in supplementary information.

Also I think a native speaker should double-check the manuscript. The use of articles and prepositions is somewhat lacking, examples I found at first sight are p1904,l13 -> "the deforestation", p1905,l21 - ->"of more than", p1906,l8 ->"In the tropical", p1907l19 "to the global", p1909,l2 ->"by an increase", p1910,l9 ->"which the relative", p1910,l24 ->"is a tendency" p1914,l7 ->"The albedo effect", p1969,l1 - ->"of the climate", p1916l2 ->"on the surface", p1916,l4 ->"of the complex" or ->"of a complex".

Furthermore, I suppose on p1908,l16 you meant "change show linearity", and I’d drop the p1910,l14 "On the contrary" -> "whereas", or such, since there is no contadiction. Disclaimer: I am not a native English speaker.

Thanks for pointing out those language issues. We have carefully edited the manuscript by our native speaker co-authors and also the editing colleagues.
References
Part 2 Revised manuscript
The role of spatial scale and background climate in the latitudinal temperature response to deforestation

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Abstract:

Previous modeling and empirical studies have shown that the biophysical impact of deforestation is to warm the tropics and cool the extra-tropics. In this study, we use an earth system model of intermediate complexity to investigate how deforestation at various spatial scales affects ground temperature, with an emphasis on the latitudinal temperature response and its underlying mechanisms. Results show that the latitudinal pattern of temperature response depends non-linearly on the spatial extent of deforestation and the fraction of vegetation change. Compared with regional deforestation, temperature change in global deforestation is greatly amplified in temperate and boreal regions, but is dampened in tropical regions. Incremental forest removal leads to increasingly larger cooling in temperate and boreal regions, while the temperature increase saturates in tropical regions. The latitudinal and spatial patterns of the temperature response are driven by two processes with competing temperature effects: decrease in absorbed shortwave radiation due to increased albedo and decrease in evapotranspiration. These changes in the surface energy balance reflect the importance of the background climate on modifying the deforestation impact. Shortwave radiation and precipitation have an intrinsic geographical distribution that constrains the effects of biophysical changes and therefore leads to temperature changes that are spatially varying. For example, wet (dry) climate favors larger (smaller) evapotranspiration change, thus warming (cooling) is more likely to occur. Our analysis reveals that the latitudinal temperature change largely results from the climate conditions in which deforestation occurs, and is less influenced by the magnitude of individual biophysical changes such as albedo, roughness, and evapotranspiration efficiency.
1. Introduction

Forests play a critical role in regulating climate through both biogeochemical and biophysical processes. Deforestation, driven by anthropogenic activities either directly, e.g., agriculture expansion, or indirectly, e.g., climate change induced disturbance (Allen et al., 2010), can result in changes in earth’s radiation balance, hydrological cycle, and atmospheric composition (Bonan, 2008). Deforestation is a major land conversion that has taken place historically over large scales and continues to be prevalent in the 21st century (Hansen et al., 2013).

Previous climate model studies highlight the interesting observation that temperature response to deforestation appears to depend on latitude (Davin & de Noblet-Ducoudré, 2010). For example, large-scale deforestation in the tropics leads to temperature increase (Nobre et al., 1991; Snyder et al., 2004; Davin & de Noblet-Ducoudré, 2010) mostly due to the strong warming effect associated with reduced evapotranspiration. However, forest removal in the temperate and high-latitude regions results in surface temperature decrease. This decrease is explained by the dominant mechanism, albedo, which increases in the cleared land and leads to lower shortwave radiation absorption (Bounoua et al., 2002; Snyder et al., 2004). This albedo-induced cooling effect is particularly strong in the boreal regions where the snow mask effect is involved (Bonan et al., 1992, 1995). In agreement with the climate model experiments, empirical studies using in-situ air temperature (Lee et al., 2011; Zhang et al., 2014) and satellite-derived land surface temperature (Li et al., 2015) also show that the temperature effects of forests have a clear latitudinal pattern.
Compared with biogeochemical effects, i.e., release of CO$_2$ to the atmosphere that warms the global climate, biophysical effects are more heterogeneous, most strongly felt at regional and local levels (Bala et al., 2007; Pitman et al., 2012), and vary with season and location (Snyder et al., 2004; Betts et al., 2007; Li et al., 2015). It is thought that biophysical effect, especially albedo and evapotranspiration, are major biophysical mechanisms through which deforestation affects temperature in latitudinal patterns (Gibbard et al., 2005). However, due to the high spatial variability of biophysical properties, the dominant mechanism and the net effect of deforestation could vary by particular location. This is further complicated by the influence of specific location’s background climate on the altered water and energy balance. For example, previous studies show that climate conditions, such as snow and rainfall, can enhance or dampen biophysical effects (Pitman et al., 2011; Li et al., 2015). Such complexity is reflected in temperate forests, where the two biophysical mechanisms with opposite effects cancel each other, making their net effect much more uncertain compared to other forests. This incomplete understanding of temperate forests was confirmed by the mixed results obtained from modeling and observational studies (Bonan, 2008; Wickham et al., 2013; Li et al., 2015). Further complication comes from deforestation-triggered changes in other energy components (such as sensible heat) and multiple atmospheric feedbacks that can modify the albedo and evapotranspiration impact. Therefore, it is important to further investigate the relative strength of albedo and evapotranspiration impact on temperature change, and how much those factors are influenced by the interaction with the local climate and other factors.
In addition to these biophysical effects, the spatial scale of deforestation is also an important factor in climatic impact. It has been shown that both spatial extent (global-regional-local) and degree of vegetation change (partial disturbance to complete removal) can alter the impact of deforestation (Sampaio et al., 2007; Longobardi et al., 2012).

Evidence for this behavior is seen in the Amazon area, where depending on the spatial scale of deforestation, precipitation change can either exhibit a linear or non-linear relationship with vegetation change (Avissar et al., 2002; Baidya Roy & Avissar, 2002; Souza & Oyama, 2010). And this relationship could even become opposite in sign (Runyan, 2012). The effect of vegetation change at various scales is still not clear on either the scale-dependency or latitudinal pattern of temperature response.

As described, the impact on temperature as a result of deforestation originates from the altered biophysical properties such as albedo, roughness, canopy conductance, surface emissivity, etc. The magnitude of some of these alterations, as well as their impact on temperature, may have inherent latitudinal patterns. For instance, the difference in albedo between forest and open land increases with latitude (Li et al., 2015). By investigating how changes to several biophysical properties contribute to temperature change, we can better understand whether the latitudinal temperature response to deforestation is either directly due to these changes, or the processes that translate these changes to the surface climate response. Efforts have been made to quantify the contribution of each biophysical factor, including both empirical (Juang et al., 2007) and modeling studies (Lean & Rowntree, 1997; Maynard & Royer, 2004; Davin & de Noblet-Ducoudré, 2010) that enable us to decompose the temperature change into components. Such studies can improve our knowledge of the mechanisms for the climate impact induced by vegetation change.
improve our knowledge on the mechanisms for the climate impact induced by vegetation change.

In this study, we use an earth system model of intermediate complexity (EMIC) to investigate how deforestation affects temperature through biophysical changes and also examine which physical mechanisms are responsible for the latitude-dependent temperature response (Section 2). To this aim, we first analyze latitudinal temperature changes in response to multiple deforestation scenarios by varying both spatial extent and deforestation fraction (Section 3.1 and 3.2). Next, we explore the possible causes for the latitudinal and spatial pattern of temperature change from both the surface energy balance (Section 3.3), as well as the background climate (Section 3.4). Finally, we show how different biophysical mechanisms affect temperature change and discuss their contributions to the latitudinal pattern (section 3.5). A brief discussion and summary are provided in Section 4.

2. Method

2.1 Model description

The UMD (University of Maryland) EMIC (Zeng, 2004) is used to perform the experiments. It consists of the global version of QTCM (Quasi-Equilibrium Tropical Circulation Model) atmosphere model (Neelin & Zeng, 2000), the physical land surface model Sland (Simple-land) (Zeng et al., 2000), the dynamic vegetation and carbon model VEGAS (VEgetation-Global-Atmosphere-Soil) (Zeng, 2003; Zeng et al., 2005), and a slab ocean model in which we use prescribed sea surface temperatures (SSTs) in our experiments.
Sland is a land surface model of intermediate complexity that is more complicated than the bucket model in its parameterization of evapotranspiration processes, aiming to model the first-order effects relevant to climate simulation. In this model, vegetation parameters such as leaf area index, roughness, stomatal conductance, and vegetation fraction depend on climate and are calculated by VEGAS. For surface albedo, seasonal climatology obtained from satellite is used as inputs (Darnell et al., 1992). Vegetation-albedo feedback is treated in the model by introducing albedo anomalies. This procedure sums the albedo change due to vegetation change (calculated by VEGAS using an empirical formula as a function of leaf area index (LAI)), and the observed albedo climatology used by the atmospheric radiation module (Zeng & Yoon, 2009). This albedo anomalies treatment prioritizes the capture of the first-order effects of albedo change due to vegetation change, since many of the possible processes that are responsible for the observed albedo are difficult to model mechanistically.

It should be mentioned that Sland in its current setup does not explicitly account for surface snow, thus no snow-albedo feedback is included. This potentially leads to an underestimation of albedo change in regions with frequent snow. However, it also offers a unique opportunity to examine mechanisms other than snow in the temperature response to deforestation at high latitudes.

The VEGAS model simulates the dynamics of vegetation growth and competition among four plant functional types (PFTs): broadleaf tree, needleleaf tree, cold grass, and warm grass. The phenology of these plants is simulated dynamically as the balance between growth and respiration/turnover. The vegetation component is coupled to land and atmosphere through soil moisture dependence of photosynthesis and...
evapotranspiration, as well as dependence on temperature, radiation, and atmospheric CO₂. The UMD EMIC has been used to study the climate and vegetation feedbacks (e.g., Zeng et al., 1999; Zeng & Neelin, 2000; Hales et al., 2004; Zeng & Yoon, 2009) and contributed to C⁴MIP, the Coupled Climate–Carbon Cycle Model Intercomparison Project, C⁴MIP (Friedlingstein et al., 2006). Figure S1 shows the potential vegetation map obtained by the end of model spin-up. The vegetation map generally has a reasonable geographical distribution but does not perfectly match modern vegetation of the real world. This is expected because the potential vegetation is derived from an equilibrium state with climate. Therefore, any differences in the simulated climate compared to modern climate or any simulation bias, for example, in precipitation (Figure S2), could influence the vegetation distribution. In addition, some bias in simulated climate is expected for a model with intermediate complexity. Such bias is tolerable in our experiments due to the focus on the climate response to vegetation change and its mechanisms as opposed to an accurate reproduction of the maximum impact of deforestation.

2.2 Experiment design

UMD earth system model is a fully coupled model, but the setup for this study is an atmosphere-land-vegetation coupled version with prescribed ocean SST, and CO₂ concentration at the preindustrial level of 280 ppm, run at a resolution of 5.625° × 3.75°. The model is driven by a climatological seasonal cycle of SST derived from HadSST (Rayner et al., 2006), averaged over 1960–1990 to smooth the influence of inter-annual climate variability. The model is first run for 500 years to allow for spin-up time during which vegetation is dynamically computed and reaches an equilibrium state with climate. Figure S1 shows the potential vegetation map obtained by the end of model spin-up. The vegetation map generally has a reasonable geographical distribution but does not perfectly match modern vegetation of the real world. This is expected because the potential vegetation is derived from an equilibrium state with climate. Therefore, any differences in the simulated climate compared to modern climate or any simulation bias, for example, in precipitation (Figure S2), could influence the vegetation distribution. In addition, some bias in simulated climate is expected for a model with intermediate complexity. Such bias is tolerable in our experiments due to the focus on the climate response to vegetation change and its mechanisms as opposed to an accurate reproduction of the maximum impact of deforestation.
of historical climate change. For our analysis, the climatology over the last 10 years of
spin-up is used as the control experiment (CTL). This is adequate for our simulation
because of the small inter-annual variability in the model.

Deforestation is imposed by setting the forest fraction in a given grid cell to the
experimental value of either zero or a percentage of its original vegetation. This replaces
the forest with bare soil, as is seen in several previous studies (Bonan et al., 1992;
Gibbard et al., 2005; Snyder, 2010). An alternative strategy of implementing
deforestation experiment is to replace trees with grass (crop). This is considered to be
more “realistic” than replacing trees with bare ground (Davin & de Noblet-Ducoudré,
2010). The conversion of trees to grass is expected to induce a similar but less
pronounced impact on climate (Gibbard et al., 2005), compared to the conversion of trees
to bare ground which would represent the maximum impact of deforestation. Despite this
difference, both strategies are frequently used in existing literature to represent
deforestation, and they yield consistent findings as the operating mechanisms and
feedbacks are the same. In the simulation for deforestation experiment, modified
vegetation fractions are fixed so that the vegetation model becomes “static” rather than
“dynamic”.

Table 1. Deforestation experiment design

<table>
<thead>
<tr>
<th>Group</th>
<th>I. Spatial extent</th>
<th>II. Deforestation fractions</th>
<th>III. Biophysical factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
<td>Tropical</td>
<td>25% global forest removal</td>
<td>Albedo</td>
</tr>
<tr>
<td></td>
<td>Temperate</td>
<td>50% global forest removal</td>
<td>Roughness</td>
</tr>
<tr>
<td></td>
<td>Boreal</td>
<td>75% global forest removal</td>
<td>Evapotranspiration</td>
</tr>
<tr>
<td></td>
<td>Global</td>
<td>100% global forest removal</td>
<td>efficiency</td>
</tr>
</tbody>
</table>
Three groups of experiments are designed to study different aspects of the deforestation impact (Table 1): (I) deforestation with different spatial extents (II) with different deforestation fractions; (III) with individual biophysical factors changed separately. The first two groups address the spatial scale problem for the climatic response to deforestation. Group (I) consists of three regional deforestation scenarios that take place in the tropical (20°S-20°N), northern temperate (20°N-50°N) and boreal (50°N-90°N) regions, and one global deforestation scenario in which all forests are cleared. Group (II) consists of four global deforestation experiments in which forest fractions are reduced as a percent to its original coverage at 25% to 100%. The 100% clearing creates the same experiment as the global deforestation in group I, labeled ALL. Group (III) is designed to separate the effect of individual biophysical factors by which deforestation affects climate. Inspired by Davin & de Noblet-Ducoudre (2010), three experiments are devised to quantify the impact from changes in albedo, roughness, and evapotranspiration efficiency. Our experiment for albedo and roughness differs from Davin & de Noblet-Ducoudre (2010), who compared the case with only “one factor changed” with the case of “everything unchanged”. In contrast, we ultimately compare the case of “everything changed with one factor unchanged” with the case of “everything changed”. Our experiments include global deforestation with albedo unchanged in “noALB”, roughness unchanged in “noRGH”, and evapotranspiration efficiency effect isolated in “EVA”. In noALB experiment, albedo change induced by forest removal is not passed to the atmosphere, which means “no albedo change” indeed in the atmosphere model since it takes observed albedo data. The other biophysical variables are still being affected by deforestation. Thus, the albedo effect can be isolated by calculating the...

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difference (ALL – noALB) between the regular global deforestation simulation (ALL) that includes the albedo change and the noALB experiment. In noRGH experiment, roughness is set to be unaffected by forest clearing, therefore, the difference ALL - noRGH can be attributed to the roughness effect. The calculation of evapotranspiration involves many parameters. For example, both albedo and roughness can affect ET.

Therefore, for EVA experiment, a different strategy is adopted by fixing both albedo and roughness (as in CTL) while other variables are allowed to change. Thus, the difference of EVA and control, EVA - CTL, reflects processes other than albedo and roughness that can affect ET, representing the pure hydrological effect of deforestation that refers to the ability of vegetation to transfer water from the soil to the atmosphere (Davin & de Noblet-Ducoudré, 2010).

All deforestation simulations are initialized with the restart files after spin-up whose vegetation map, relevant parameters, and model codes have been modified as described above. Each simulation is run for 100 years and the averaged results of the final 10 years are used for the analysis. Ground temperature is used to analyze temperature change, because the model does not output the 2-m air temperature. Ground temperature has a strong signal of the locally induced temperature change, which is closely coupled to the surface energy balance. This enables us to focus on the local and regional impacts of vegetation change. Only model grid points with forest fractional change larger than 0.1 are analyzed for robustness. The resulting changes in LAI, albedo, and roughness, induced by global deforestation, are provided in Supplementary Information (Figure S3–S5).
3. Results

3.1 Latitudinal temperature change in response to deforestation

Figure 1. Ground temperature change for (a) tropical (20°S-20°N), (b) northern temperate (20°N-50°N), (c) boreal (50°N-90°N), and (d) global (90°S-90°N) deforestation (Unit: K).

The latitude dependence of temperature response is confirmed by the three regional deforestation experiments (see Figure 1a-c for tropical, northern temperate and boreal, and Figure 1d for global deforestation experiments). The deforestation impact in the simulation is a very strong signal relative to the small inter-annual variability, making almost all changes over the land statistically significant. Therefore, significance levels are not shown on the map. In tropical deforestation (20°S-20°N) experiment, a significant
and widespread warming is observed over deforested regions by 2.22 K (Table 2),
greatest (~4 K) in the Amazon and Central Africa regions and about 1-2 K in South Asia
and the east coast of Australia. Although warming is the dominant effect, there are areas
around Sahel, North Africa in which we observe cooling up to -2 K. This suggests
temperature response can differ within a latitude band, as shown in earlier studies
(McGuffie et al., 1995; Snyder et al., 2004). The regional difference is partly due to the
regional circulation patterns being affected differently by deforestation (McGuffie et al.,
1995). Temperature outside the deforestation boundary (e.g., South Asia, North Canada)
is also influenced by the tropical deforestation, indicating that the vegetation disturbance
signal can spread to distant regions through atmospheric processes. Replacing forest with
bare ground leads to a surface albedo increase of 0.26, and a decrease of shortwave
absorption at the surface by 38 W/m². Precipitation and evapotranspiration also decline
drastically by 3.75 and 2.93 mm/day, respectively, while sensible heat increases.
Reducing cloud cover results in an increase in downward shortwave and a decrease in
downward longwave radiation (Table 2).

In the northern temperate region (20°N-50°N), deforestation causes a temperature
decrease of -0.84 K over most areas. North China and most parts of the United States
show the largest cooling (~1.5 K) while a weaker cooling (< -1 K) is observed in Europe.
Nevertheless, temperature rise can be found in some areas like South China (1-2K) and
Southeast U.S. (~1 K), similar to the tropics. The regional difference also reflects the
different response of the surface energy balance to deforestation, and is related to the
background climate as discussed in the next section. Other changes, including increased
albedo and decreased shortwave absorption as well as decrease in ET and precipitation,
can be seen in temperate deforestation, but the magnitudes are much smaller than those in the tropics. Unlike the tropical region, sensible heat decreases in the temperate region and is consistent with the sign of temperature change.

Compared with the temperate region, deforestation in the boreal region results in a stronger cooling of -1.70 K but changes in the surface energy components are much smaller. It should be noted that albedo only increases by 0.22 because of no snow-masking effect in the land surface model, which could enhance the cooling signal by amplifying the albedo change. Nevertheless, a considerable cooling is seen in our results without the snow-masking effect, suggesting that other changes rather than snow contribute to the cooling effect of deforestation.

Table 2. Changes in key climate variables from regional and global deforestation experiments. “Δ” denotes change relative to the control experiment. The value for each climate variable is the area-weighted change over deforested areas for different latitude zones. The symbol “↑” denotes upward and “↓” denotes downward. Units are W/m² for energy flux, K for temperature, mm/day for precipitation, and unitless for albedo.

<table>
<thead>
<tr>
<th></th>
<th>Tropical (20°N-20°S)</th>
<th>Temperate (20°N-50°N)</th>
<th>Boreal (50°N-90°N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Regional</td>
<td>Global</td>
<td>Regional</td>
</tr>
<tr>
<td>Temperature</td>
<td>2.22</td>
<td>2.06</td>
<td>0.84</td>
</tr>
<tr>
<td>Precipitation</td>
<td>-3.75</td>
<td>-3.89</td>
<td>0.81</td>
</tr>
<tr>
<td>ET</td>
<td>-82</td>
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<td>-17</td>
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<tr>
<td>Sensible heat (ΔH)</td>
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<td>13</td>
<td>12</td>
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<tr>
<td>Shortwave (ΔSW₁)</td>
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<td>18</td>
</tr>
<tr>
<td>Shortwave (ΔSW)</td>
<td>88</td>
<td>95</td>
<td>41</td>
</tr>
</tbody>
</table>
3.2 Sensitivity of temperature change to spatial extent and degree of vegetation change

The influence of spatial extent of deforestation can be clearly seen by comparing the temperature response in a given region under regional and global deforestation experiments. While similar in spatial pattern, temperature change in the global deforestation experiment (Figure 1d) is much stronger than those in the regional deforestation, especially in mid and high latitudes (Table 2). From the regional to global scale, deforestation-induced cooling increases from -0.84K to -1.56K, and from -1.70K to -2.42 K in the northern temperate and boreal regions, respectively. In contrast, warming in the tropics is less affected and even slightly decreases from 2.22K in the regional deforestation case to 2.06K in the global case. This is because global deforestation leads to a stronger reduction of both absorbed shortwave radiation and downward longwave radiation, both amplifying the cooling effects (Table 2) that reduce tropical warming and enhance high-latitude cooling. Such dampened tropical warming and enhanced extratropical cooling from regional to global deforestation experiments are supported by a recent study (Devaraju et al., 2015). Overall, an amplified temperature change in the global deforestation experiment is expected as it generates a stronger perturbation in the
atmosphere, but the latitudinal temperature response is well preserved despite the increase in the spatial extent of deforestation from regional to global.

By looking at a set of experiments with varying deforestation fractions, we found temperature change is also sensitive to degree of vegetation change (see Figure 2, Table 3). Deforestation fraction refers to the percentage of trees removed relative to the original coverage (25%, 50%, 75%, and 100%), which is representative of the real areas that have been deforested. For 25% deforestation fraction, temperature is virtually unaffected in most areas except for a weak warming in the tropics. As forest-loss fraction goes up to 50%, a latitudinal temperature change emerges with discernible tropical warming and weak cooling in mid and high latitudes (Figure 3). Higher deforestation fractions of 75% and 100% result in a greater temperature change and a more prominent latitudinal pattern.

Generally, the magnitude of temperature change responds non-linearly to increases of deforestation fraction, with much larger changes at high deforestation fractions (Figure 3, Table 3). This non-linearity can either arise from the response of biophysical land parameters to deforestation, or from the climate response (i.e., temperature response) to biophysical changes. We found nonlinearities in both of these aspects (Figure S6).

Generally, the magnitude of temperature change responds non-linearly to increases of deforestation fraction, with much larger changes at high deforestation fractions (Figure 3, Table 3). This non-linearity can either arise from the response of biophysical land parameters to deforestation, or from the climate response (i.e., temperature response) to biophysical changes. We found nonlinearities in both of these aspects (Figure S6).
Figure 2. Temperature change for global deforestation experiments with different deforestation fractions at (a) 25%, (b) 50%, (c) 75% and (d) 100%
albedo.

W/m² for energy flux, K for temperature, mm/day for precipitation, and unitless for albedo.

Table 3. Changes in key climate variables from global deforestation with different deforestation fractions. “∆” denotes change relative to the control experiment. The value for each climate variable is the area-weighted change over deforested areas for different latitude zones. The symbol “↑” denotes upward and “↓” denotes downward. Units are

<table>
<thead>
<tr>
<th>Region</th>
<th>Tropical (20°N-20°S)</th>
<th>Temperate (20°N-50°N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deforestation fraction</td>
<td>25% 50% 75% 100%</td>
<td>25% 50% 75% 100%</td>
</tr>
<tr>
<td>Temperature</td>
<td>0.53 1.22 1.86 2.06</td>
<td>0.03 -0.23 -0.75 -1.64</td>
</tr>
<tr>
<td>Precipitation</td>
<td>0.58 1.51 2.83 2.89</td>
<td>-0.17 -0.49 -0.71 -0.93</td>
</tr>
<tr>
<td>ET</td>
<td>-15.3 -37.1 -59.2 -85.5</td>
<td>-4.6 -12.4 -17.4 -20.7</td>
</tr>
<tr>
<td>Sensible heat (AH)</td>
<td>12.0 23.2 27.8 33.3</td>
<td>2.4 0.9 -4.1 -13.3</td>
</tr>
<tr>
<td>Shortwave (ΔSW)</td>
<td>3.8 13.1 27.1 52.6</td>
<td>1.7 7.7 14 21.3</td>
</tr>
</tbody>
</table>

Figure 3. Latitudinal pattern of temperature change with different deforestation fractions.
Temperature change is driven by altered surface energy balance in response to forest removal. Among them, changes in shortwave radiation absorption (ΔSW) and evapotranspiration (ΔET) can largely determine the sign and magnitude of temperature response to deforestation. Deforestation can increase surface albedo, leading to reduced absorbed shortwave radiation at the surface (ΔSW) which acts as a cooling mechanism, while decreased ET (ΔET) can produce a warming effect due to weakened latent cooling.

Figure 4c shows the latitudinal pattern of ΔSW and ΔET. Although the largest decreases are observed in the low latitudes and become smaller as latitude increases, the relative importance of these two varies across latitudes as also reported in Davin & de Noblet-Ducoudre (2010) and Li et al. (2015). In the tropics, ET declines (warming effect) more than the absorbed shortwave radiation (cooling effect). This ΔET-dominated energy imbalance is compensated by increase in temperature, outgoing longwave radiation, and sensible heat. Beyond the tropics, the opposite occurs, as ET declines less than absorbed shortwave radiation, therefore temperature and sensible heat decrease in response to the ΔSW-dominated energy imbalance. Specifically, mid latitude is a transition region where ΔET and ΔSW in the south are relatively close to each other but in the north are quite different. In high latitudes, ΔET is negligible whereas ΔSW maintains similar magnitude as in the mid latitudes, thus resulting in the most significant temperature decrease.

Although ΔSW and ΔET determine the basic latitudinal pattern of temperature change, changes in downward longwave radiation (ΔLW↓) and sensible heat (ΔH) also have
influence. While $\Delta SW \downarrow$ (changes in downward shortwave) could be considered as a part of atmospheric feedback due to cloud cover change, we find that $\Delta SW$ is still dominated by $\Delta SW \uparrow$ (changes in upward shortwave) due to albedo change (Figure S7). $\Delta LW \downarrow$ decreases across all latitudes due to less cloud cover, while sensible heat increases in the tropics and decreases in other latitudes. $\Delta LW \downarrow$ is combined with $\Delta SW$ to give the available energy ($\Delta Ava=\Delta SW+\Delta LW \downarrow$) and $\Delta H$ is combined with $\Delta ET$ to give the turbulence energy ($\Delta Tub=\Delta ET+\Delta H$), corresponding to the change in received and dissipated energy, respectively. Available energy warms the land surface while turbulence energy cools the surface (de Noblet-Ducoudré et al., 2012). The difference of these two is the outgoing longwave radiation, which is a function of ground temperature, and is equivalent to ground temperature change. As shown in Figure 4d, the latitudinal changes of the available and turbulence energy largely resemble that of $\Delta SW$ and $\Delta ET$, but with some noticeable differences. Comparing with $\Delta SW$, reduction in available energy ($\Delta Ava$) is larger across all latitudes, suggesting an amplifying feedback mechanism through $\Delta LW \downarrow$ due to reduced cloud cover (more reduction in $\Delta SW+\Delta LW \downarrow$, Figure 4a). However, $\Delta Tub$ is smaller than $\Delta ET$ in the tropics (less reduction for $\Delta ET+\Delta H$, Figure 4b) but larger than $\Delta ET$ in the mid and high latitudes (more reduction for $\Delta ET+\Delta H$, Figure 4b), showing that the warming signal can be either weakened or enhanced when $\Delta H$ is considered (see Table 2). Overall, the latitude pattern of $\Delta SW$ and $\Delta ET$ in the southern hemisphere is influenced more by $\Delta LW \downarrow$ and $\Delta H$ than in the northern hemisphere. In the southern hemisphere, the originally large energy difference between $\Delta SW$ and $\Delta ET$ disappears when $\Delta LW \downarrow$ and $\Delta H$ are accounted for, resulting in a dampered energy difference of $\Delta Ava$ and $\Delta Tub$. 
Figure 4. Latitudinal pattern of changes in surface energy balance. (a) Changes in absorbed shortwave radiation ($\Delta SW$), downward longwave radiation ($\Delta LW_{↓}$), and available energy ($\Delta Ava=\Delta SW+\Delta LW_{↓}$). (b) Changes in evapotranspiration ($\Delta ET$), sensible heat ($\Delta H$), and turbulence energy ($\Delta Tub=\Delta ET+\Delta H$). (c) $\Delta SW$ and $\Delta ET$. (d) $\Delta Ava$ and $\Delta Tub$

Analysis above shows that the basic latitudinal pattern of $\Delta SW$ and $\Delta ET$ can explain most of the latitudinal temperature response regardless of other changes and feedbacks (e.g., changes in downward longwave radiation and sensible heat). Here we evaluate the extent to which relative importance of $\Delta SW$ and $\Delta ET$ can explain the spatially varying temperature change in terms of its sign and amplitude. The sign of temperature change can be approximated by a simple ratio of $\Delta ET/\Delta SW$. The accuracy of this approximation depends on the strength of the basic pattern imposed by $\Delta SW$ and $\Delta ET$ against other
changes. A larger-than-one ratio suggests ∆ET warming exceeds ∆SW cooling and temperature is likely to increase, whereas a smaller-than-one ratio suggests ∆SW cooling is stronger than ∆ET warming and temperature tends to decrease. We used results from the regional deforestation numerical experiments to demonstrate this feature. Figure 5 shows the deforested grid points in the model with their ∆ET and ∆SW plotted on the x and y axes, with colors representing the sign of temperature change. Deforested points with increased temperature (red) are often located in the upper-left space of the ∆ET = ∆SW line where warming is anticipated (∆ET > ∆SW), while points with decreased temperature fall into the lower-right space where cooling is anticipated (∆ET < ∆SW). It turns out that ∆ET and ∆SW alone can explain 93%, 88%, and 99% of deforested points for the direction of temperature change in the tropical, temperate, and boreal regions, respectively. In addition, there is tendency towards smaller ∆ET/∆SW ratios at higher latitudes and drier areas in the global deforestation experiment (Figure S8), suggesting a decreasing importance of ∆ET over ∆SW. Few exceptions exist because longwave and sensible heat changes may also influence temperature change but are not considered here. Furthermore, the amplitude of temperature change is related to the difference of ∆SW and ∆ET. As shown in Figure 5d-f, ∆SW - ∆ET is highly correlated with the amplitude of temperature change in the tropical (r=0.96) and temperate regions (r=0.79), but not in the boreal region (r=0.27).
Figure 5. Changes in ET (ΔET), absorbed shortwave radiation (ΔSW) and their relationship with temperature change (ΔT) over deforestation areas. (a-c) Deforested points with their ΔSW, ΔET, and the sign of ΔT. The upper left area means ET warming exceeds albedo cooling; the lower right area means albedo cooling exceeds ET warming. Blue (red) are the actual grid points where temperature decreased (increased). Number denotes the percentage of deforested points whose sign of ΔT agrees with anticipation of...
ΔSW and ΔET. (d-f) Spatial relationship between ΔSW-ΔET and the amplitude of ΔT. Red line is the regression line, and r is the correlation coefficient. (a,d) Boreal deforestation. (b,e) North temperate deforestation. (c,f) Tropical deforestation.

3.4 Influence of background climate on surface energy change and temperature change

The latitude-dependent pattern for ΔSW and ΔET could arise from the intrinsic latitudinal distribution in background climate, e.g., solar radiation and precipitation/ET decrease with latitude increase. Therefore, the same amount of albedo change would translate into a larger ΔSW in lower latitudes due to the geographic distribution of solar radiation. Likewise, given the same ET reduction rate, a larger ΔET is expected in the tropics than in high latitudes.

The influence of background climate can be illustrated by a simple calculation. Assume that deforestation causes albedo increase by 0.02, 0.05, 0.12, and 0.23 uniformly across all latitudes and ET decrease by 15%, 30%, 50%, and 75% compared to their baseline climatology, respectively. Multiplying these change rates by the baseline shortwave radiation and ET, we obtain the corresponding ΔSW and ΔET without considering any climate feedback. For demonstration purpose, the change rates chosen here for albedo and ET roughly correspond to the global averaged changes in the four deforestation fraction experiments (deforestation fraction ranges from 25% to 100%, see group II experiment). Interestingly, the calculated ΔSW and ΔET (Figure 6) agree well with the simulation (Figure 4c). The main features, including ΔET > ΔSW in the tropics and ΔET < ΔSW in the extratropics, are captured. We also used the satellite derived ET and shortwave radiation data from Li et al. (2015) to perform the calculation (see Figure...
The results generally support the findings from Figure 6, except for the two combinations with small changes in albedo and ET. For these two cases, the anticipated pattern is not captured mainly because of the chosen low albedo change in high latitude, which leads to an underestimation of ∆SW. It should be emphasized that the albedo and ET change rates in reality have more complicated patterns than what we assume in the calculation. Nevertheless, our simple calculation still reveals the role of the baseline climate in shaping the latitude-dependent temperature change to deforestation.

Figure 6. The latitudinal pattern of ∆SW and ∆ET calculated by multiplying their background climate values with different rates for albedo (red number, from 0.02 in (a) to 0.23 in (d)) and ET changes (blue number, from -15% in (a) to -75% in (d)). In (d),...
Further evidence comes from the spatial relationship between background climate and temperature response to deforestation. We found baseline precipitation is highly correlated with $\Delta ET$ ($r=-0.98$) and with $\Delta T$ ($r=0.87$), suggesting that precipitation can influence temperature change by controlling ET change. This is also supported by the ratio of $\Delta ET/\Delta SW$ in Figure S8 where larger $\Delta ET$ over $\Delta SW$ is found in wetter areas, and by observations from air temperature (Zhang et al., 2014) and physical mechanisms pertaining to soil moisture (Swann et al., 2012). Therefore, spatial variation of temperature change is partly due to background climate. For instance, temperature decreases in the tropical deforested areas like Sahel, west Amazon, and southwestern Africa, because dry climate limits $\Delta ET$, thus temperature change is dominated by the cooling effect from $\Delta SW$. In contrast, in wet temperate deforested areas like South China, India, and parts of North America, temperature increases because of the dominant warming effect from $\Delta ET$.

3.5 Contribution of individual biophysical processes to the latitudinal temperature change

The aforementioned changes in temperature and surface energy balance are triggered by the altered biophysical variables such as albedo, roughness, ET efficiency, etc. as a result of deforestation. The effect of each individual biophysical factor and its contribution to temperature change are evaluated in this section.

(1) Albedo
The impact of albedo change can be isolated by the difference of ALL – noALB (see Method Section), as shown in Figure 7a. As expected, albedo change causes significant temperature decrease over all affected regions. Surprisingly, the strongest cooling appears in the northern temperate region instead of the tropics where the largest albedo increase occurs (Table 4). This indicates the strength of perturbation is not the only factor for determining spatially varying temperature change. The magnitude of cooling in the boreal region is similar to the temperate region, because of no amplified albedo change due to snow. If deforestation did not change albedo, there would be a substantial warming over all affected regions (noALB – CTL, Figure 7b), accompanied with decreased ET and very little change in absorbed shortwave radiation (SW). This is expected because the warming effect of ΔET dominates temperature change when albedo effect is absent.

Figure 7. (a) Impact of Albedo (only) on temperature change (b) temperature change without albedo impact (K)

(2) Roughness
Roughness can affect turbulence (ET as well as sensible heat) flux between land surface and atmosphere. Higher roughness facilitates absorbed shortwave energy to be dissipated as turbulence, while smaller roughness suppresses this process and could have a warming effect. Effect of roughness on climate can be isolated by the difference All – noRGH. Roughness change as well as its impact are more pronounced in the tropical region (Table 4). As is seen in Figure 8a, reduced roughness warms most areas except for the upper northern latitudes, with warming decreasing from the tropics to high latitudes; see also Davin & de Noblet-Ducoudre (2010). Without roughness change, deforestation would cause less warming (Figure 8b) and less reduction in turbulence energy (not shown) than regular deforestation. Moreover, Figure 8b also shows the combined effects from albedo and evapotranspiration efficiency since roughness effect is excluded. Thus, the existence of a tropical warming in some regions implies that the reduction in evapotranspiration efficiency remains dominant and outweighs the albedo impact in this situation.

Figure 8. (a) Impact of roughness (only) on temperature (K); (b) temperature change without roughness
(3) Evapotranspiration efficiency

Evapotranspiration efficiency refers to the ability of partitioning available energy into evapotranspiration more than into sensible heat. The conversion of forest to bare land favors more turbulence energy to be transferred in the form of sensible heat rather than ET, resulting in higher Bowen ratio. The impact of altered ET efficiency can be separated by EVA – CTL, showing a noticeable warming in the tropical regions and some parts of the temperate region, and negligible impact in high latitude (Figure 9). It seems that changed ET efficiency has a significant impact only over regions with wet climate, which may be due to the close coupling between precipitation and ET change.

Figure 9. Evapotranspiration efficiency impact on temperature change (K)
Table 4. Summary of influence of individual biophysical factors on temperature change. Numbers in parentheses are changes in albedo and roughness. Albedo is unitless and unit for roughness is m.

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<tr>
<th></th>
<th>Global (ALL – CTL)</th>
<th>Albedo (ALL – noALB)</th>
<th>Roughness (ALL-noRGH)</th>
<th>Evapotranspiration efficiency (EVA – CTL)</th>
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</thead>
<tbody>
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<td>50°N-90°N</td>
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<td>-2.93 (0.22)</td>
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<td>0</td>
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<tr>
<td>20°N-50°N</td>
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<td>-3.1 (0.18)</td>
<td>0.86 (0.66)</td>
<td>0.27</td>
</tr>
<tr>
<td>20°S-20°N</td>
<td>2.06</td>
<td>-1.92 (0.28)</td>
<td>1.92 (1.33)</td>
<td>1.22</td>
</tr>
</tbody>
</table>

All: global deforestation; noALB: global deforestation without albedo change; noRGH: global deforestation without roughness change; EVA: global deforestation without both albedo and roughness change.

By summing up the contributions from individual biophysical factors linearly (ALL – noALB + ALL – noRGH + EVA – CTL), we reconstruct temperature change, which closely agrees with the actual signal (ALL – CTL) in terms of both latitudinal (Figure 10) and geographical patterns (Figure 11). Latitudinal features are inherited in the contribution of each individual component (Table 4). Albedo effect generally increases with latitude whereas roughness and evapotranspiration efficiency effects decrease with latitude. Therefore, the largest temperature increase in the tropical region (2.06K) originates from the warming effect of changed roughness (1.92K) and evapotranspiration efficiency (1.22K), and is counteracted by a comparatively small albedo cooling (-1.92K).

In the extratropics, temperature response is dominated by albedo cooling, with similar strengths in the northern temperate (-3.01K) and boreal (-2.93K) regions. But such cooling is partially canceled by the weaker warming effect of roughness (0.86K) and evapotranspiration efficiency (0.27K) in the temperate region and no compensation at all.
in the boreal region. The latitudinal pattern caused by each biophysical factor is less likely to be due to the latitudinal signal from biophysical change per se, because biophysical change does not match the latitude pattern of temperature response. For example, the largest temperature change does not occur where the largest biophysical change (e.g., albedo and roughness) occurs. This shows the complex interactions in the translation from the initial perturbation to subsequent climate response, which varies by latitude. Biophysical impacts are strongly regulated by the baseline climate where vegetation change occurs, as also demonstrated in Pitman et al. (2011).

Figure 10. (a) Latitudinal patterns of the contribution of individual biophysical factors to temperature change and (b) reconstructed temperature change from individual biophysical effects (SUM=ALL- noALB + ALL- noRGH + EVA- CTL)
4. Discussion

Our results show patterns of temperature change as a result of deforestation that are in line with the conclusions of previous modeling studies, e.g., strong tropical warming (Nobre et al., 1991; Snyder et al., 2004), moderate temperate cooling, and strong boreal cooling (Bonan et al., 1992, 1995; Betts, 2000), but few of them consider the spatial scale of deforestation. We found that temperature change varies nonlinearly with both the spatial scale and the fraction of forest removed, with increasingly larger temperature change as disturbance grows, but the overall latitudinal pattern is not altered. This scale-dependent relationship between temperature change and deforestation reflects a perturbation-response relationship derived from the existing mechanisms of the model in which non-linearity is found. However, it does not exactly emulate the influence of physical processes operating at various scales in the real world, because many scale-related processes cannot be fully resolved in a model with a fixed complexity. For...
example, many meso-scale processes cannot be included in a global model. This makes it difficult to compare our results to observational study results that span different spatial scales.

We found that changes in shortwave radiation absorption (ΔSW) and evapotranspiration (ΔET) can largely determine the sign and amplitude of temperature change, as well as its latitudinal and spatial patterns in response to deforestation. In a global deforestation scenario, more than 90% of the sign of temperature change over deforested areas can be explained by ΔSW and ΔET. Although ΔET and ΔSW can be influenced by other factors and feedbacks, they still provide useful diagnostic information for temperature change and serve as a first order approximation. Using this information, albedo and ET changes (two variables readily available from satellite data) can be potentially applied to evaluate the possible impact of undergoing land cover change on local and regional temperature (Loarie et al., 2011; Peng et al., 2014; Li et al., 2015).

To a large extent, the latitude-dependent temperature response to deforestation and its spatial variability can be attributed to background climate condition, such as solar radiation, precipitation, and snow, which in turn affect the biophysical impact of vegetation change. Further evidence comes from the contribution of each biophysical factor, i.e., albedo, roughness, and ET efficiency, on the temperature response. Although these factors drive temperature change in different directions, their contributions also have clear latitudinal patterns (Davin & de Noblet-Ducoudre, 2010). This indicates that climate condition manifests its influence either explicitly in the temperature response through controlling changes on surface energy balance, or implicitly in the magnitude of biophysical alteration triggered by deforestation. After careful analysis of our model, our...
results show that the latitudinal pattern of temperature change is due to the explicit impact of climate condition.

We acknowledge certain limitations and important issues that are not fully addressed in this study. Previous studies showed an important role of oceanic feedback which could cause additional cooling through albedo change (e.g., sea-ice albedo feedback) and could override temperature change over land in mid latitudes (Claussen et al., 2001; Davin & de Noblet-Ducoudré, 2010), but our ocean model is not interactive so such dynamics could not be studied here. Another question is the temperature variable used for studying the deforestation impact. Ground temperature instead of air temperature is analyzed here due to our model structure. Although air temperature is more widely used in the climate science community,

Furthermore, in this study we use ground temperature as the variable for accessing the deforestation impact. In other studies, and perhaps more commonly, this component could be analyzed using air temperature, although research based on ground temperature (McGuffie et al., 1995; Kendra Gotangco Castillo & Gurney, 2012) or surface temperature (Davin & de Noblet-Ducoudré, 2010) is also seen in the literature. Although these two have been shown to often agree with one another at larger scales (Jin et al., 1997), it is worth investigating whether they have different responses to vegetation...
change (Baldocchi & Ma, 2013; Zhao & Jackson, 2014; Li et al., 2015). Moreover, the
response of maximum and minimum temperatures also differ from the daily averaged
temperature (Zhang et al., 2014; Li et al., 2015), a problem that has received less
attention in modeling studies.

Finally, results from a single model are subject to uncertainty and some features might
be model-dependent. For instance, some biases in the simulated climate of the model may
lead to shifts in vegetation distribution and thus could influence the deforestation impact.

To combat this, model inter-comparison projects like Land-Use and Climate,
Identification of Robust Impacts (LUCID) experiments (Pitman et al., 2009) can help to
distinguish robust findings against model uncertainty. The participant models in LUCID
show consistency in how land cover change affects available energy but diverge greatly
on energy partition between latent and sensible heat flux changes (de Noblet-Ducoudré et
al., 2012), indicating large uncertainty lies in the response of non-radiative process to
land cover change, especially for ET (Boisier et al., 2012). Therefore, considerable effort
is required to improve model performance in the simulation of land processes, and new
inter-comparison projects such as LUMIP (Land Use Model Intercomparison Project,
https://cmip.ucar.edu/lumip) are highly valuable. In addition, observational studies are
indispensable as they can offer new insights and serve as a reference benchmark for
model results, especially those using new techniques and datasets such as satellite data.

Author contributions:

Y. Li designed and carried out the experiments; Y. Li and N. De Noblet-Ducoudré
analyzed the data; all authors contributed to the discussion and writing of the paper.
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References:


**Supplementary figures:**
Figure S1. Simulated vegetation distribution in the control experiment (CTL)
Figure S2. Annual mean precipitation simulated in the control experiment.
Figure S3. Spatial (left) and latitudinal (right) patterns of LAI changes due to global deforestation (Unit: m²/m²)
Figure S4. Spatial (left) and latitudinal (right) patterns of albedo changes due to global deforestation.
Figure S5. Spatial (left) and latitudinal (right) patterns of roughness changes due to global deforestation (Unit: m)
Figure S6. (a) Response of albedo change to growing deforestation fraction from 25% to 100% and (b) temperature response to albedo change under different deforestation fractions. Data points in the figure are from Table 3.
Figure S7. Latitudinal changes in downward ($\Delta SW_{\downarrow}$), upward ($\Delta SW_{\uparrow}$) and absorbed shortwave radiation ($\Delta SW$)
Figure S8. Ratio of ΔET/ΔSW in global deforestation
Figure S9. ∆SW and ∆ET calculated with MODIS ET and shortwave radiation (data from Li et al. (2015))