Reply to reviewers' comments

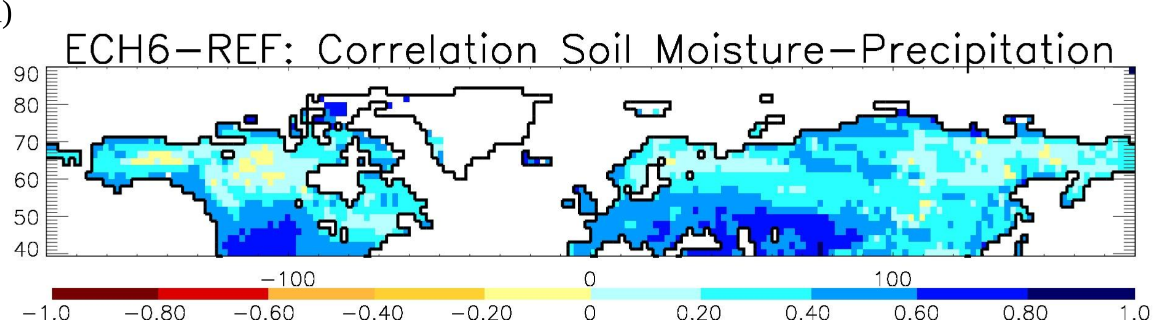
We thank Rene Orth and the anonymous reviewer for their thorough reading of the manuscript and their valuable remarks that helped us to improve the manuscript. In the following, the original reviewer comments are given in *italic* and all line numbers refer to the submitted version that was reviewed if not mentioned otherwise.

Reply to review of Rene Orth:

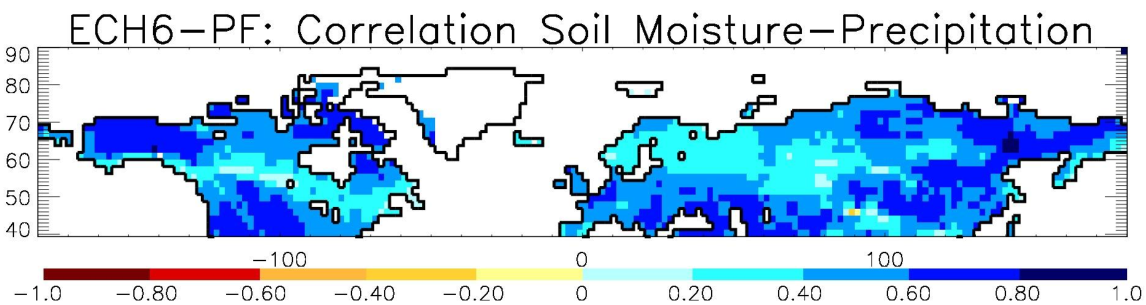
One main comment concerns the proposed soil moisture-precipitation feedback. While this feedback seems to be a plausible explanation of the reported results, more analysis is needed to confirm its operation. There may be many ways to do this, I could think of the following: Compute correlations between soil moisture and precipitation using seasonal values from all available years at any particular location. The resulting correlation maps for each simulation could be insightful.

Thank you for this suggestion. To add further analysis, we calculated the correlations between soil moisture and precipitation using monthly values from 1989-2009 for ECH6-REF and ECH6-PF. Then, we calculated the difference between correlation maps (ECH6-PF minus ECH6-REF). The resulting map (Fig. R1c) shows that the correlation between soil moisture and precipitation is strongly increased in ECH6-PF over large parts of the northern high latitudes, especially over North America and eastern Siberia. This confirms the enabled soil moisture-precipitation feedback we identified over the northern high latitudes and for the area of the six largest Arctic catchments.

a)



b



c)

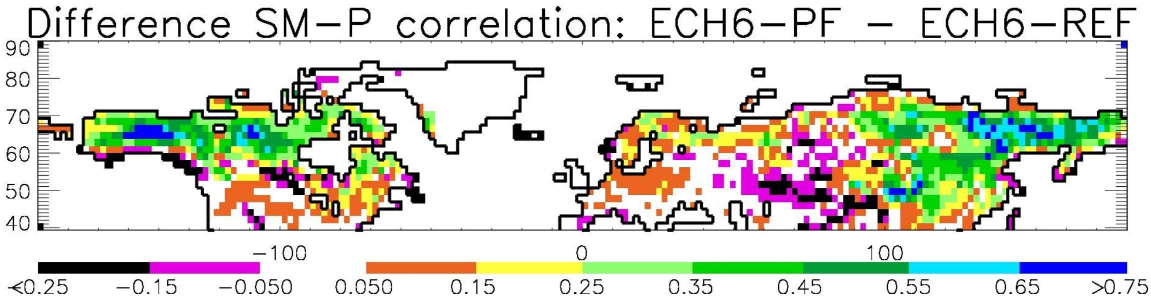


Fig. R1: Correlation of soil moisture and precipitation for a) ECH6-REF, b) ECH6-PF, and c) difference between ECH6-PF and ECH6-REF.

We will add the figure and associated text in Sect. 4, starting in line 345:
In order to support our finding of this positive soil moisture-precipitation feedback, we calculated the correlations between soil moisture and precipitation using monthly values from 1989-2009 for both experiments. While there are higher correlations between soil moisture and precipitation in the mid-latitudes for ECH6-REF (Fig. R1a), the high latitudes are mostly characterized by rather low correlations. Figure R1b and c show that the correlation between soil moisture and precipitation is strongly increased in ECH6-PF over large parts of the northern high latitudes, especially over North America and eastern Siberia. This confirms an increased coupling of soil moisture and precipitation, and, hence, also indicates the soil moisture-precipitation feedback we identified. This positive ….

Furthermore I am missing discussion and reasoning on the fact that the hydroclimatic changes following the introduction of the new PF scheme also occur in warmer regions (eg. aggravating the temperature bias in central North America and southern Russia). Why is that? Why is it not possible to adapt the model modifications to prevent such effects? And in essence, is it more than a trade of model performance in one region against another region?

Changes in hydrological cycle are mostly confined to areas where melting and freezing of water play a role. To illustrate this, Fig. R2 shows the number of months where in the climatological average of 1989-2009, the upper soil layer is below 0°C in ECH6-PF. Changes in precipitation (Fig. 2, see also new Fig. 2c in reply to reviewer 1) and surface solar irradiance (Fig. 4, see also new Fig. 4c in reply to reviewer 1), indicating changes in cloud cover, are mostly located in regions where the upper layer is frozen for at least three months within the climatological average.
Changes outside of regions with soil frost may be imposed by changed atmospheric humidity and heat transport from soil frost affected regions on the one hand. On the other hand, the JSBACH-PF soil scheme also introduces a constant soil organic layer. This layer was implemented everywhere by Ekici et al. (2014) (in the future, it is planned to extend the layer by a more dynamic module) and has an isolating effect also outside of soil frost regions. Thus, in the summer, less parts of the available energy at the surface enter the soil via the ground heat flux so that this increases the turbulent fluxes, in particular the sensible heat flux. This in turn contributes to the warming of the 2m air temperature which can be seen also in areas without any soil frost (Fig. 3, see also new Fig. 3c in reply to reviewer 1).

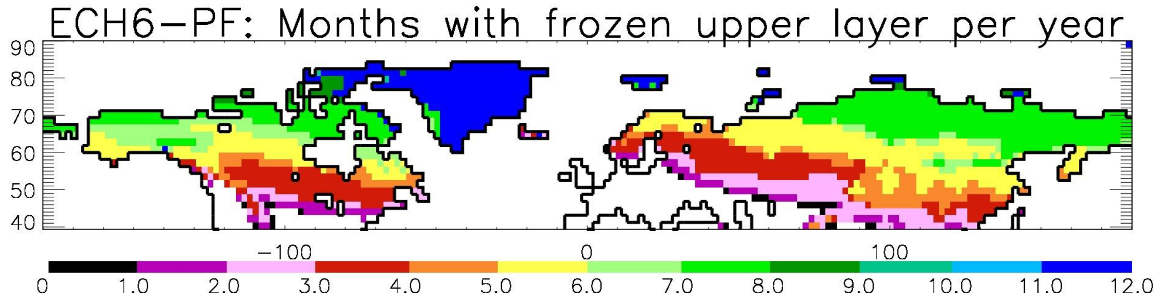


Fig. R2: Number of months where in the climatological average of 1989-2009, the upper soil layer is below 0°C in ECH6-PF.

We will add this discussion in Sect. 4 as a new paragraph starting in line 351.

Another general comment refers to the terminology used in the paper. The authors should state more clearly that they refer to liquid moisture if they use 'soil moisture'.

In end of Sect. 2.1, we will add the following text:
"Note that in the following the term soil moisture generally refers to the liquid soil moisture if not mentioned otherwise. In this respect, total soil moisture refers to the sum of liquid and frozen soil moisture. "
In addition, we will thoroughly check the usage of the corresponding terms throughout the manuscript.

Furthermore Figures 6 and 10 present results already contained in Figures 2-4. I understand the motivation of the authors to first present a global picture and to then focus on particular regions. However, maybe the text describing these figures can be shortened to be less repetitve.

We will shorten the text describing Figures 6 and 10.

Specific comments

line 24: insert 'the' before MPI-ESM
It will be corrected as suggested.

line 45: please explain 'Pg of C'
Here, we will update the text by more recent results from line 41 onwards and also clarify the use of "Pg of C":
… high carbon contents (Ping et al., 2008, Nature Geoscience) leading to a total pan-Arctic estimate of 1300 Pg of soil carbon (C) in these areas (Hugelius et al., 2014, Biogeoscience), which is twice the amount of the atmosphere's content. Moreover, the high …

line 57: CH4 does not simply 'become' CO2
We will modify the text:
… after which it is converted to CO2 by oxidation.

line 82: replace ', which' with '. The parameterizations'
It will be corrected as suggested.

line 107: What is the ’potential rate’?
We will modify the text:
…at the potential rate imposed by the atmospheric conditions, i.e. the potential evapotranspiration.

line 126: abbreviation ESM was introduced earlier
We will modify the text:
… components of the ESM of the …

lines 143/144: How can properties ’decrease’?
Soil hydraulic conductivity and diffusivity are hydraulic properties of the soil. They depend on soil moisture and, hence, may increase or decrease when soil moisture increases or decreases, respectively.

We will modify the text:
… content may decrease when soil moisture freezes (such as, e.g., the hydraulic conductivity).

line 145: delete ’now’
It will be corrected as suggested.

line 146: confusing sentence, please rephrase
We will modify the text:
In the original snow scheme, the snow is thermally growing down inside the soil, i.e. the snow cover becomes part of the soil temperature layers so that soil temperatures are mixed with snow temperatures. In the new scheme, snow is accumulated on top ….

line 154: replace ’for’ with ’during’
It will be corrected as suggested.

lines 154/155: delete ’so that’
It will be corrected as suggested and a ‘,’ will be inserted instead.

line 156: if it is switched off anyway why do you mention it?
It is switched off in the default application of JSBACH3, but not in our study as setting this switch is hydrologically more sensible, and GPP is not of interest in the present study.

lines 178-180: Please clarify if you are using the WATCH or the WFDEI forcing data.
We are only using WFDEI. We will modify the text:
… the recent global WATCH dataset of hydrological forcing data (WFDEI; …

line 194-195: How do your results differ if you consider all ET datasets instead of only the diagnostic datasets?
We chose to compare our simulated ET only with the diagnostic estimates of ET, not with other model data. If considering the ET from all datasets, the ET over the six largest Arctic river catchments is rather similar to those from the diagnostic estimates, especially in the summer (Fig. R3).

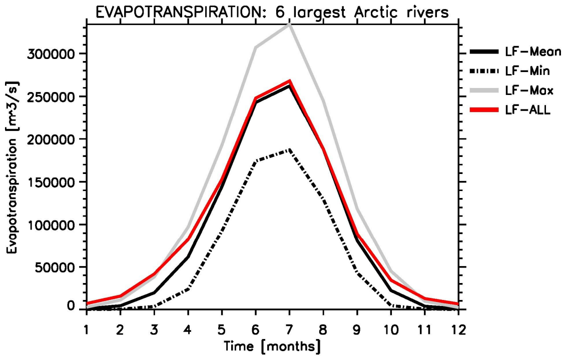


Fig. R3: Mean ET of all LF datasets compared the mean, minimum and maximum diagnostic estimates from the LandFlux Eval (LF) dataset.

line 217: why the fifth layer? and how deep is that?
As the upper layers usually thaws during the summer (the maximum thawing depth is called active layer depth), we chose the lowest layer of the JSBACH soil column, which is certainly below the active layer. Its depth is ranging from 4.13 m to 9.83 m.

We will add the following text to the model description in Sect. 2.1.line 136:
These five layers correspond directly to the structure used for soil temperatures and they are defined with increasing thickness (0.065, 0.254, 0.913, 2.902, and 5.7 m) down to a lower boundary at almost 10m depth.

line 222: insert 'to' before 'avoid'
It will be corrected as suggested.

line 228 and elsewhere: please use consistent simulation names (ECHPF/ ECH6-PF)
We will thoroughly check for the usage of ECH6-PF, which we intended to use throughout the paper.

lines 234/235: 'evaluated ... to the evaluation'?
We will modify the text:
…latitudes analogously to how the evaluation of surface water and energy fluxes of the CMIP5 version of MPI-ESM was conducted by Hagemann et al. (2013b).

line 301/302: Problem with brackets
We will modify the brackets:
[Note that a version of MODIS albedo data was used where low quality data over the very high northern latitudes were filtered out in the boreal winter due to too low available radiation (A. Löw, pers. comm., 2016). Due to these missing data over mainly snow covered areas, MODIS albedo averaged over the six largest Arctic rivers is biased low in the winter].

line 339: Please clarify that the spring soil moisture deficit from increased discharge extents into the summer thanks to the soil moisture memory (e.g. Koster and Suarez 2001, Orth and Seneviratne 2012)
We will modify the text and add:
This spring soil moisture deficit from the increased discharge extents into the boreal summer due to the soil moisture memory (e.g. Koster and Suarez 2001, Orth and Seneviratne 2012), when it actually causes …

line 361/362: This is wrong, these studies compute diagnostics at seasonal time scales!

We agree with regard to Koster et al. (2004) as here we mixed something up. We disagree with regard to Teuling et al. (2009). For the results described in their Fig. 1, they explicitly note: "In Figure 1 we display the correlation of ET with incident solar (global) radiation (Rg), respectively precipitation (P), on the yearly timescale in the GSWP-2 reanalysis."

We will modify the text, starting in line 361:
… (Seneviratne et al., 2010). But on the one hand it can be assumed that many models participating in those earlier studies did not include the melting and freezing of soil water. Thus, our reference simulation ECH6-REF is in line with results reported in the literature, generally not showing a strong coupling between precipitation and soil moisture in permafrost regions, such as indicated by the rather low correlation values in Fig. R1a. Only the ECH6-PF simulation using advanced soil physics shows that such strong coupling indeed is present (Fig. R1b). On the other hand, only annual mean diagnostics were considered in some of those earlier studies (e.g. Teuling et al., 2009). In other land-atmosphere coupling studies, that, e.g., followed the GLACE protocol such as Koster et al. (2004), prescribed soil moisture conditions were used that were similar to the average soil moisture climatology. Here, it seems that the differences between the simulations with free and prescribed soil moisture in GLACE type simulations may be not large enough to reveal a large-scale feedback over the high latitudes. This may only be possible by an experimental design where more pronounced summer soil moisture changes are introduced. Note that in the present study, these pronounced changes were introduced not due to an artificial design, but they were caused by the implementation of previously missing frozen soil physics into the model. Our study has shown that spring moisture deficits can lead to soil moisture conditions during the boreal summer that allow for an advanced land atmosphere coupling and a positive soil moisture-precipitation feedback over the northern high latitudes.

lines 388/389: replace 'not an issue' with 'beyond the scope of the present study'
It will be corrected as suggested.

Figure 1: It almost seems to me as if the new parameterization leads to too little permafrost extent.
We agree with the reviewer. This is consistent with the already existing (in ECH6-REF) and increased (in ECH6-PF) warm bias.

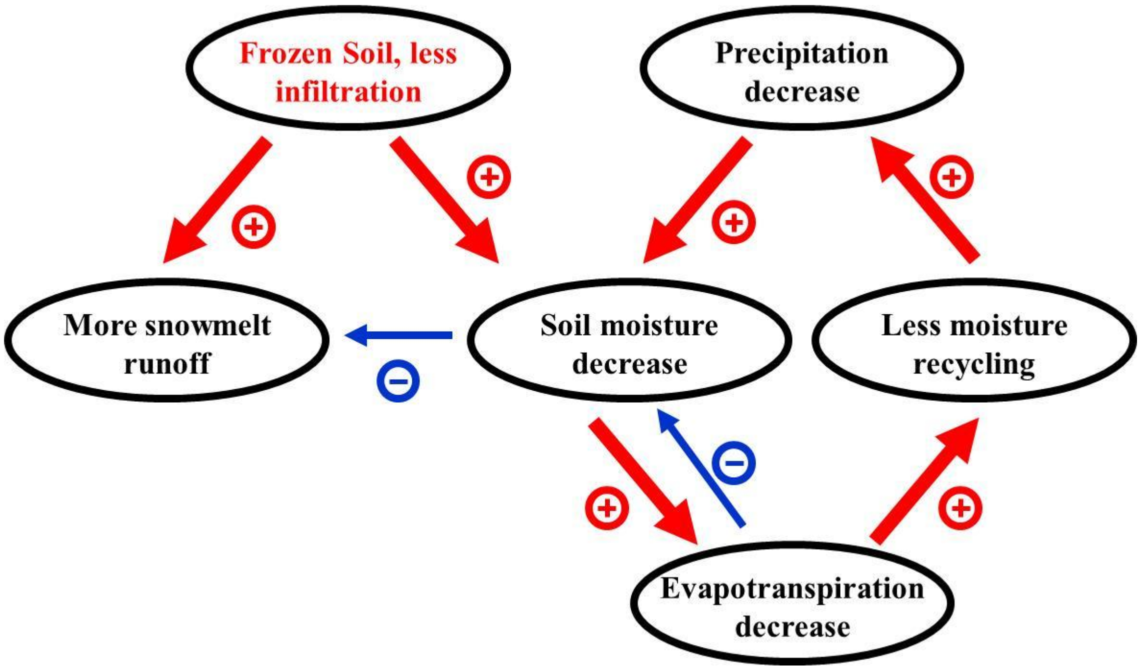
Figures 1-4: please label the color bars
We are somewhat puzzled by this remark as the colour steps are already labelled, and variable and unit are provided in the figure captions except for Fig. 1. For Fig. 1, we will add:
…permafrost areas [%] in ….

Figure 7: include dashed blue line in legend
It will be included as suggested.

Figure 8: repetitive titles, no x-axis label
We will remove the title above the figure panel, but the x-axis is already labelled with 'Time [months]'.

Figure 12: Your line of arguments is that first the soil freezes and then more runoff occurs such that consequently soil moisture is decreased. This is not clear from this scheme.

We have redrawn the scheme so that it starts now with the soil freezing on the left:



New Fig. 12. Chain of processes involved in the soil moisture precipitation feedback over high latitudes. Red arrows indicate directions supporting this feedback, blue arrows indicate compensating opposite effects.