Reply to anonymous reviewer 1:

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. Following our general reply, the original reviewer comments are given in *italic* and all line numbers refer to the submitted version that was reviewed if not mentioned otherwise. Note that the numbering of new figures (R1,…) does not correspond to the sequence of appearance within this response as we wanted to provide consistent figure numbers with our response to the review of Rene Orth.

General reply

According to the remarks of reviewer 1 we feel that our current text may have led to a partial misunderstanding. We don't propose that soil freezing and melting processes lead to a new feedback, but that these processes enable a known feedback to become active over the northern high latitudes. In order to avoid a possible misunderstanding we will modify the title, the abstract as well as the beginning and the end of the discussion section as follows:

New title:
Soil frost-enabled soil water precipitation feedback over northern high latitudes

Modified abstract: starting in line 13
… permafrost. The currently observed global warming is most pronounced in the Arctic region and is projected to persist during the coming decades due to anthropogenic CO2 input. This warming will certainly have effects on the ecosystems of the vast permafrost areas of the high northern latitudes. The quantification of such effects, however, is still an open question. This is partly due to the complexity of the system, including several feedback mechanisms between land and atmosphere. In this study we contribute to increasing our understanding of such land-atmosphere interactions using an Earth system model (ESM) which includes a representation of cold region physical soil processes, especially the effects of freezing and thawing of soil water on thermal and hydrological states and processes. The coupled atmosphere-land models of the ESM of the Max Planck Institute for Meteorology, MPI-ESM, have been driven …

and line 28:
… subsequent reduction of soil moisture enables a positive feedback …

Modified discussion section, starting in line 330:
The results described in the previous section show that soil freezing and thawing processes enable the positive soil moisture-precipitation feedback over large parts of northern mid- and high latitudes during the boreal summer. The chain of processes leading to and influencing this feedback …

Modified discussion section, starting in line 409:
We have shown that soil physical processes such as thawing and freezing have an impact on the regional climate over the high latitude permafrost areas. Flato et al. (2013) reported that CMIP5 GCMs tend to overestimate precipitation over northern high latitudes except for Europe and western Siberia. As many of these GCMs are still missing basic cold region processes, a missing interaction between soil moisture and precipitation in those GCMs is

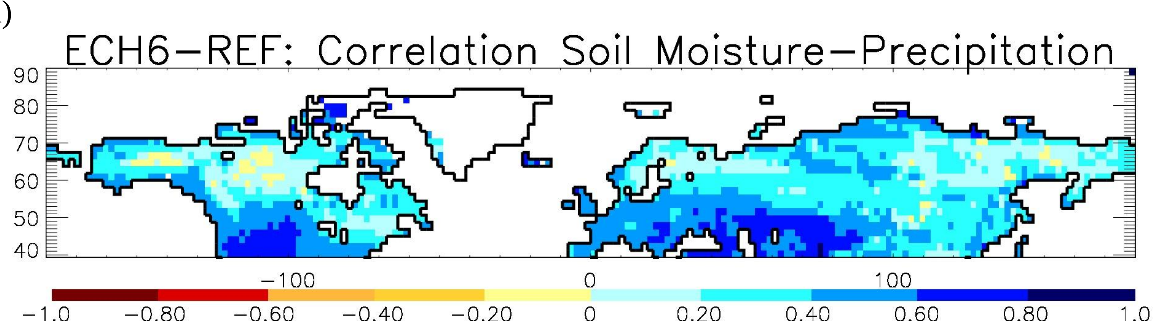
likely to contribute to this wet bias. An adequate implementation of physical soil processes into an ESM is only the first necessary step to yield an adequate representation of land-atmosphere interactions over the high latitudes. This also includes the incorporation of wetland dynamics, which will be the next step in the JSBACH development with regard to high latitudes, thereby following an approach of Stacke and Hagemann (2012). In addition, a reliable hydrological scheme for permafrost regions will allow investigations of related climate-carbon cycle feedback mechanisms (Heimann & Reichstein, 2008, Nature).

Specific reply

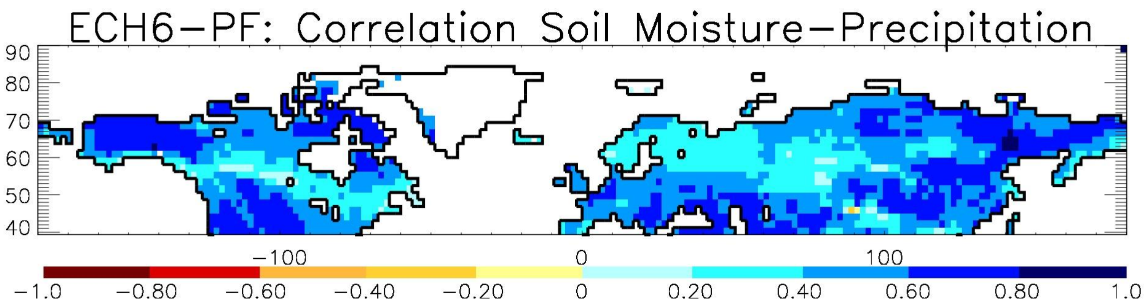
Although the set-up of the experiment and the discussion of the results are well done and straightforward, I find some of the conclusions somewhat speculative. First, the existence of this positive feedback cannot be diagnosed very well from comparing two (ensemble) simulations of different model configuration. An experimental design is required in which this feedback loop is explicitly affected, which is not the case here.

We agree that additional analyses are helpful to support our conclusions. But we don't think that additional experiments need to be set up (see also our reply to the comment below). In this respect, we follow the advice of Rene Orth, the other reviewer of our manuscript, who suggested considering correlations of soil moisture and precipitation. Consequently, 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)

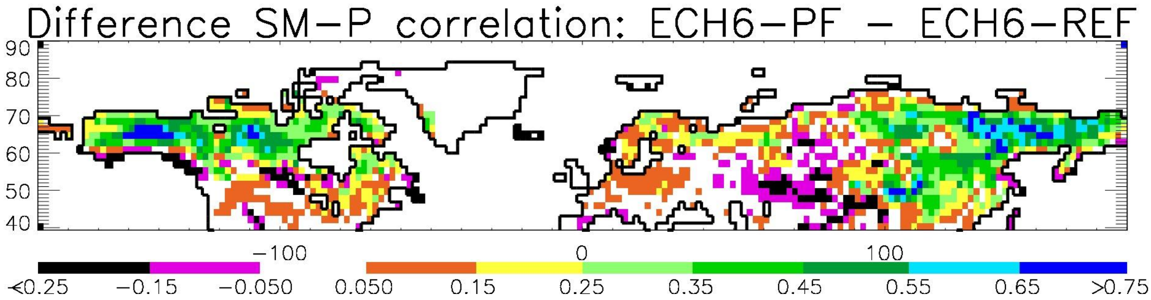


Fig. R1: Correlation of soil moisture and precipitation for a) ECH6-REF, b) ECH6-PF, and c) difference between ECH6-PF and ECH6-REF.

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 ….

It is surprising that earlier feedback studies as the ones by Koster et al and a few successors did not pick up this positive feedback in this area, in spite of targeting the same summer season as discussed extensively by the authors.

In order to add more discussion to this issue, 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.

Also, such a positive feedback, when present, does require a sufficient amount of energy to generate a reasonable hydrological cycle. It should be shown that a significant fraction of available energy is not used for precipitation, by computing a kind of Budyko index.

Here, we are not 100 % sure if we correctly understand the reviewer's comment. The coupled atmosphere-land surface component of MPI-ESM used here, is based on differential equations representing physical first principles and comprises closed energy and water budgets. Thus, no energy and water are lost or generated within the system. Consequently, both model versions, with and without freezing/thawing are fully consistent with respect to the closed budgets. This means that there must be sufficient energy available to generate the simulated hydrological cycle, which also looks reasonable in ECH6-PF (e.g. Fig. 6 a, c, Fig. 7a).

We calculated the Budyko index following Arora (2002, The use of the aridity index to assess climate change effect on annual runoff, J. Hydrology 265: 164-177) as the available energy R_{net} (annual mean net radiation at the surface) divided by precipitation P and the latent heat of vaporization L for both experiment. The corresponding maps (Fig. R4) show that for ECH6-PF, the high latitudes generally get somewhat more arid than for ECH6-REF. This is consistent with the identified feedback loop where the reduced soil moisture leads to reduced summer precipitation. We don't think that this provides much additional information so we would not include this figure in the manuscript.

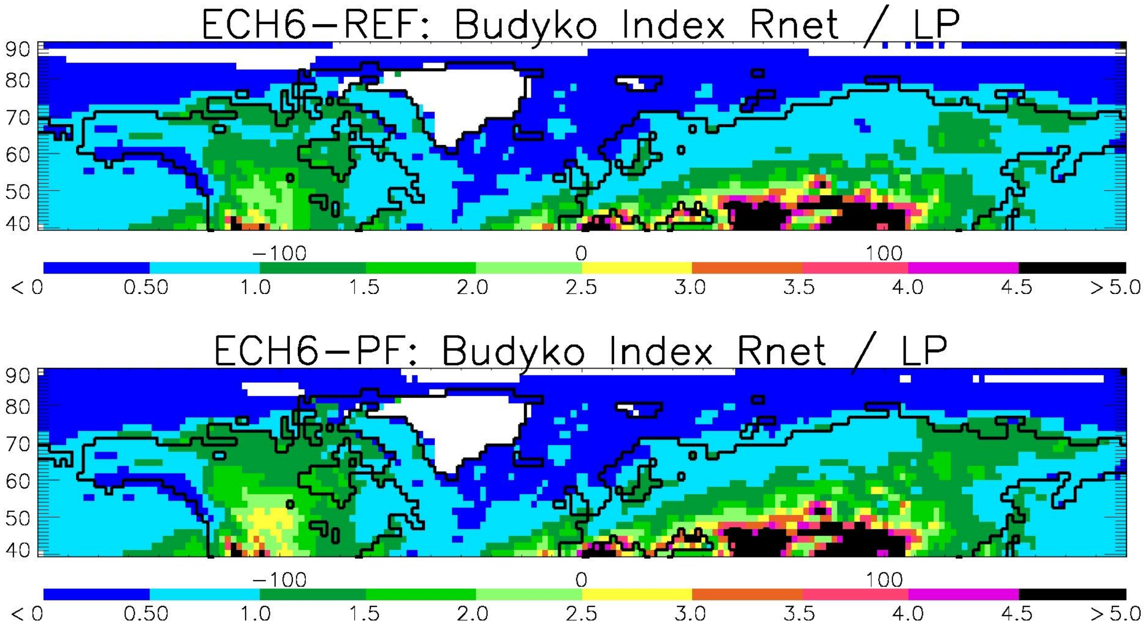


Fig. R4: Budyko dryness index for ECH6-REF (upper panel) and ECH6-PF (lower panel) derived from annual mean net surface radiation and precipitation.

Second, it is somewhat unclear why the large effects of the new scheme also tend to extend to areas where snow and permafrost occurrence is much less pronounced. Apparently strong alterations of the scheme to the entire soil hydrological balance are imposed.

Changes in the 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 below) and surface solar irradiance (Fig. 4, see also new Fig. 4c below), 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 new JSBACH-PF soil scheme also introduces a constant soil organic layer. This layer was implemented everywhere by Ekici et al. (2014) 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 below).

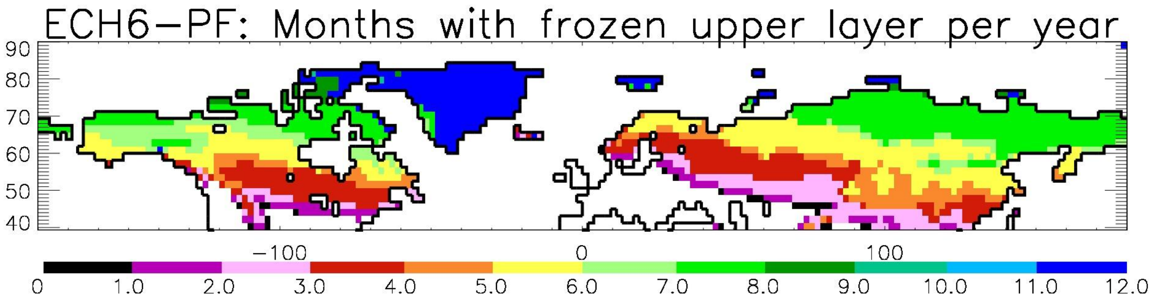
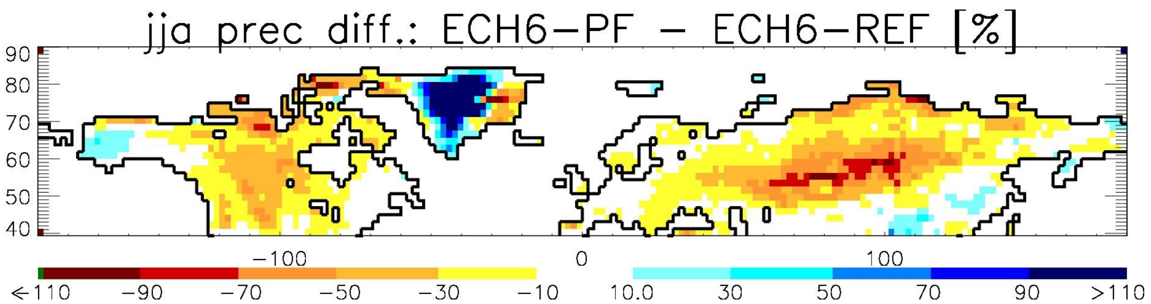


Fig. R2: Number of months where in the climatological average of 1989-2009, the upper soil layer is below 0°C in ECH6-PF.

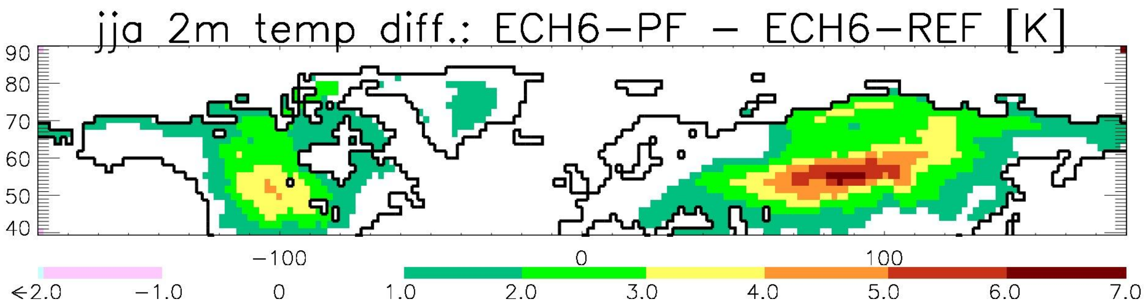
We will add this discussion in Sect. 4 as new paragraph starting in line 351.

For both notions a different presentation of results would be favorable. Particularly figs 2-4 should be presented as a difference between the 2 model versions rather than (or in addition to) the difference to observations. This provides a better connection to fig 12, and allows a discussion on the spatial structure of the supposed feedback.

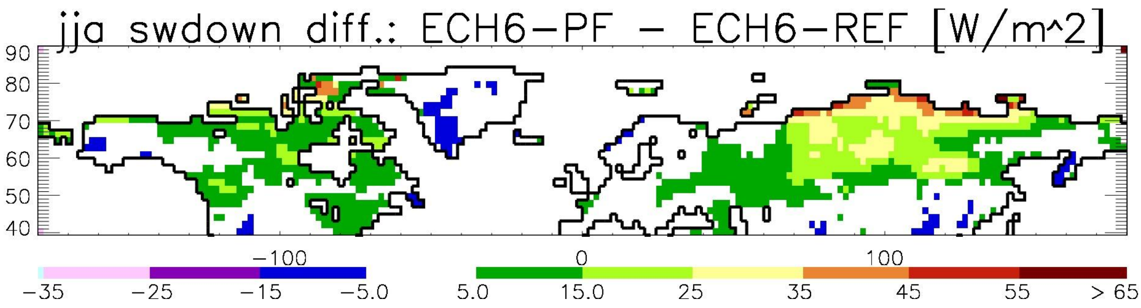
As suggested, we will add a third panel to each of the figs. 2-4 that shows the respective differences between the two experiments. These difference maps are shown in the following as the new figures 2c, 3c and 4c.



New Fig. 2c: Precipitation difference between ECH6-PF and ECH6-REF in [% of WFDEI precipitation].



New Fig. 4c: 2m temperature difference between ECH6-PF and ECH6-REF.



New Fig. 5c: Surface solar incoming radiation difference between ECH6-PF and ECH6-REF.

Specific comments

L57: "becomes CO2" sounds a bit odd
We will modify the text:
… after which it is converted to CO2 by oxidation.

L76: whereat -> whereas
It will be corrected as suggested.

L108: excluded from
It will be corrected as suggested.

Fig 1: the difference in permafrost area is not very clear nor impressive

On the one hand, a validation of the simulated permafrost area is not the focus of the present study as this has been done by Ekici et al. (2014). They forced the JSBACH land surface scheme offline with prescribed quasi-observed forcing and showed that winter temperatures were underestimated if only liquid water exists in the model, i.e. if no thawing/freezing is considered. On the other hand, we think that it is indeed rather good that there is no large difference, as it implies that no really huge differences have been imposed to the simulated climatological energetic mean state of the soil through the use of the new PF scheme. In other words, the use of physical cold region soil processes does not necessarily imply a completely different permafrost distribution. Note that the permafrost map is generated through diagnosing permafrost purely from a soil temperature criterion. Thus, already the soil temperatures in ECH6-REF yield a reasonable permafrost distribution. Actually the new PF scheme leads to too little permafrost extent, which is consistent with the already existing (in ECH6-REF) and increased (in ECH6-PF) warm bias.

L362: Koster et al 2004 did not present annual means but JJA means
Yes, we agree. Here, we mixed something up and will modify the text (see also response to your second major comment).

L406: the advection of warm air is also of influence on the recycling ratio that is computed. You should address this aspect
We will modify the text in lines 405-406:
Further contributions to this warm bias might be related to a too weak vertical mixing of heat within the boundary layer of too much advection of warm air. The latter may also influence the recycling ratio of water within and outside regions of soil frost.

Fig 6: the dark blue and black colors are too similar to be distinguishable
We will carefully check this issue with ESD as after some previous colour optimization we have successfully used the present combination of dark blue and black (with the used line thickness) in several publications. We will modify the blue if recommended by ESD.

Fig 8: which model is shown here? Why only one model?
We only show results for ECH6-PF, since ECH6-REF does not include any freezing, and, hence no frozen soil moisture. We will add the following text:
…soil moisture (1989-2009) in ECH6-PF over the … … curve). Note that for ECH6-REF, this is zero as no freezing is regarded.

Fig 12: what is the role of temperature in this diagram? It seems an important variable
We agree that temperature plays a role for freezing and melting of soil moisture. But for this hydrological feedback loop that is initiated by the introduction of frozen soil, temperature does not play a first order active role. Its secondary effect is a general warming (less cooling of the surface due to the reduced evapotranspiration, more heating of the surface to the increased incoming solar radiation induced by the lower cloud cover – see also, e.g., lines 288-294).
In order to mention its general importance for soil freezing and thawing processes, we will add the following in line 350:

Since air temperature is a main driver of soil freezing and thawing processes, there are more indirect interactions between energy and water balances which call for even more advanced factorial model experiments in the future.
A positive …