

## Response to reviewer 1

We thank the reviewer for their helpful comments. Please find below our response and details of the corrections to the manuscript. (Reviewer's comments in black and our comments in blue).

The use of 'permafrost' and 'near-surface permafrost' is a bit unclear in the text. The authors can state upfront the definition for near-surface permafrost and use it where appropriate. *Page 1980, Line3: '....is less than 3m for the preceding two years is assumed to have permafrost'. Definition of permafrost and near-surface permafrost to be provided in the text upfront. Page 1984, Line18: 'all permafrost points (a) and all points (b)'. I think this should be near-surface permafrost points and all permafrost points.*

Thanks for the comment. We see this wasn't very clear in the text. We have now stated it more clearly, replacing page 1980, line 3: "Our definition of near-surface permafrost is a grid-cell with ALT less than 3 m for two or more consecutive years.", and we have added the words 'near-surface' in all places where it is relevant.

The experiments orgmossD and orgmossDS differ in SWE. The authors indicate that in the old zero-layer snow scheme, the insulation from snow was incorporated in the top layer of the soil. How exactly is this done? What about the hydrology part? This is not clear from reading the text. I would suggest that the authors add few more lines to clarify this in this text.

To address this question we have firstly re-written section 2.2.4 as follows: "In the original multi-layer snow scheme, numerical stability requires that the layered snow is only used when the snow depth is 10 cm or greater, and the old, zero-layer snow scheme is used for shallower snow. The modification introduced in Chadburn et al. (2015) allows the multilayer snow scheme to run with arbitrarily thin layers, thus removing the zero-layer snow scheme from the model altogether.

In the zero-layer snow scheme the heat capacity of snow is neglected and melt water is passed directly to the soil model to be partitioned into infiltration and runoff. In the multilayer snow scheme the snow is treated as a separate layer with its own heat capacity, and a fraction of the mass in a snow layer can be retained as liquid water instead of passing straight into the soil model. This water will freeze if the layer temperature falls below 0°C. Thus the snow mass will be slightly different in the multilayer scheme, and in general the model's behaviour is more realistic."

And secondly, see the next comment (below) for an explanation of the conductivity in the zero-layer scheme.

Page 1970, Lines 12 to 18: How are snow thermal conductivity and albedo modelled? Please provide related information.

Snow in the zero-layer scheme has a constant thermal conductivity that is added in series to the conductivity of the top layer of soil. In the multi-layer snow model, thermal conductivity is parametrized as a function of snow density. Snow albedo is parametrized as a function of snow grain size (Best et al. 2011). -- We have added this to the text in Section 2.1.

The authors show and discuss figures that demonstrate the impact of the new developments on the soil thermal regime, but I did not find any discussion on the soil hydrologic regime. Some discussion in this regard should be there in the article as the soil thermal and hydrologic regimes are tightly linked.

We agree that there should be more discussion of the hydrology. In fact the hydrology in JULES requires much more work and detailed investigation (see for example Chadburn et al. (2015) in Geoscientific Model Development – here we show some of the coupling with soil temperatures). We have made some comments about this in the conclusion:

"[...these limit the potential to improve the snow representation at present.]

Soil moisture is also important for soil temperatures, and the two are linked in a complex manner. Water has a higher thermal conductivity than air, so in wetter soils, more heat will penetrate and leave the ground. However, if there is soil freezing and thawing, the latent heat will reduce the rate of heat penetration, counteracting this effect. Furthermore, if there is soil freezing the mean temperature in the deeper soil is colder than that at the surface, since the thermal conductivity of ice is greater than that of water, so more heat moves upwards in winter than downwards in summer. The influence of soil temperature on soil moisture mainly comes from freezing, as this prevents moisture running out of the soil and may also hold liquid water above a permafrost layer.

Between the runs in this paper, the main differences in soil moisture come from organic soils, which increase the soil moisture content overall. To disentangle the complex impacts requires more specific experiments than the ones in this study, such as an experiment where specific influences of soil moisture on temperature are removed. Further investigation of the hydrology in JULES is vital and this is the subject of ongoing work.”

The simulations for current climate is driven by WATCH forcing dataset and those for future simulations, starting in 2006, are driven by adding future climate anomalies from CCSM4 to the meteorological forcing, for two scenarios. It would be useful to show these anomalies, particularly for summer temperature and SWE, for the two scenarios, since these are the most important factors controlling near-surface permafrost evolution. *Page 1976, Line15: As indicated under general remarks, provide plots for the projected changes to SWE and summer temperature.*

We agree with the reviewer about this and we have added such a plot (see Fig. 1, below) and added the following discussion in the text: “The anomalies for air temperature and precipitation are shown on Figure 3. There is not a large trend in precipitation, although in RCP 8.5 there is a small increase, along with an increase in variability. Air temperature, on the other hand, shows a clear increase by the end of the century, up to 10°C in RCP 8.5. The change in air temperature is much larger in winter than in summer.”

Page 1967, Lines 7 to 9: ‘Additional new processes... ..modification to the snow scheme’ can be modified to make clear that the sensitivity of permafrost to these new developments are investigated in this study.

Thanks for the suggestion. We have changed this sentence to read: “Additional new processes within JULES, the land surface scheme of the UK ESM (UKESM), include a representation of organic soils, moss and bedrock, and a modification to the snow scheme and the sensitivity of permafrost to these new developments is investigated in this study.”

Page 1971, Lines 18 to 20: The authors mention that the soil column is 10 m deep in all experiments except min4l and min14l. What is the reason behind choosing 10 m? For most of the pan-Arctic region, it is going to be smaller than that, at the resolution used in this study. Previous studies have either used constant depths in the range of 3 to 4 m or they vary in space according to available datasets. If these experiments were to be repeated with soil column in the 3 to 4 m range, there could be important changes, isn’t it?

We chose a 10m soil column to make sure we include all of the latent heat and to diagnose the deep active layer depths. However, maybe you are right that a smaller soil column would be more realistic. To investigate the impact, we have in fact done another historical simulation with a 3m soil column and bedrock (instead of a 10m soil column and bedrock). The results show that actually it doesn't make a big difference. See below for plots comparing this alternative simulation (called 'min14l\_deep') with the minD simulation, shown on Figures 3 and 4 (below). The main difference is there are no active layers larger than 3m as this is now the base of the soil column. We conclude that it is a minor difference compared with the difference with/without bedrock. In future we would like to change the model to use the available spatial datasets, as the reviewer suggests, but this requires

an extremely big change to the model functioning so it is beyond the scope of this paper, and the plots below show that it does not make a large difference. Lawrence et al. (2008) find a similar result in CLM: “simply including versus omitting the deep soil layers (e.g., including or omitting the deep ground heat sink) has a far bigger impact on the soil temperature simulations than the specification of the deep soil properties.”

We have referenced this in the text, and justified the choice in Section 2.2.1, adding: “10m was chosen as a large value, to make sure that all of the freeze-thaw dynamics would be captured.”

“In fact, soil is often shallower than 10m and the bedrock should start at varying depths depending on the spatial location, but initial tests showed that starting the bedrock at 3m instead of 10m made a very small difference compared with the impact of including a deep heat sink or not, and the same has been shown in other models, such as in Lawrence et al. (2008).”

The experiments with deeper configuration include bedrock. The depth of this layer and thickness of layers should be indicated here in the text, though the information can be found in Table 2.

We have added the following in Section 2.2.1 to clarify this: “The number and thickness of bedrock layers is set by the user when running the model. In this study, the bedrock column was run with 100 layers of 0.5 m each, making a 50 m column, thus bringing the total soil column up to 60 m.”

And also adding in Section 2.5: “When deeper soil is added in minD, this includes both the extension of the soil column to 10m and the addition of a 50m bedrock column.”

Figures:

Figure 2: Difficult to distinguish between shrub tundra and boreal forest in the top panel. Maybe this occurred during the creation of the pdf file.

The colours seem quite different in my version, but it can sometimes depend on the pdf reader. To make sure there is no confusion we have changed it to purple and made the regions more well-defined on the map. See Fig. 2, below.

Figure 8: ‘.....permafrost points only: this includes only those points with ALT less than 3m:.... 70% thaw to 3m or deeper.’ What is the range of ALTs that you got for this 70% points?

Thank you for this comment, we realise this was not an accurate statement. The 70% of 'non-permafrost' points include all the other grid cells in the simulation, which includes many points where the soil column doesn't freeze, which means that saying they 'thaw to 3m or deeper' was misleading! We have re-phrased as follows:

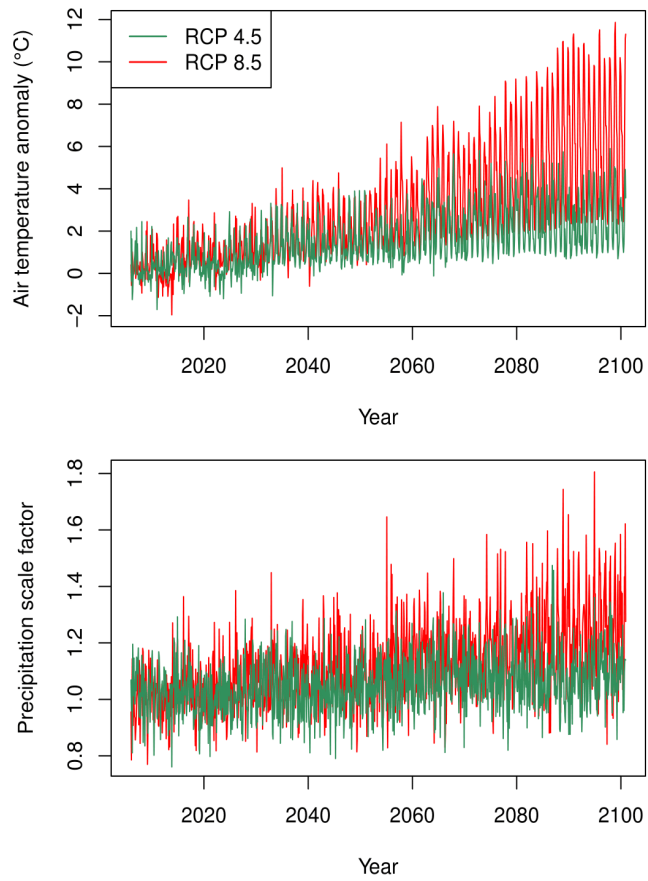
OLD: “On Fig. 9b the amount of permafrost with active layer less than 3 m in each simulation is apparent from the fraction of points that thaw to less than 3 m (generally about 30% of points).” --->

NEW: “On Fig. 9b the amount of near-surface permafrost in each simulation is apparent from the fraction of points that thaw to less than 3 m (generally about 30% of points).”

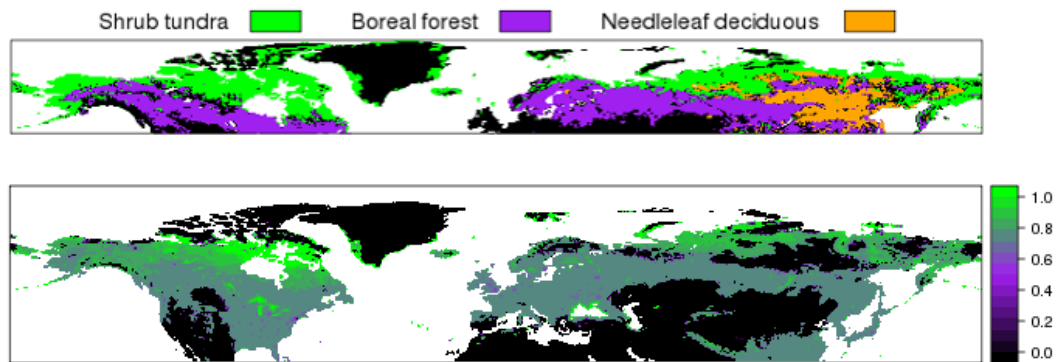
“b) All points included, hence about 70% thaw to 3 m or deeper.” --->

“b) All points included, so about 70% thaw to greater than 3 m or have no permafrost at all.”

The range of ALT's for such points is therefore anything between 3m and 10m (the base of the soil column), or not defined.



*Figure 1: Temperature and precip anomalies - plot added to manuscript.*



*Figure 2: Updated colours on the Euskirchen vegetation map.*

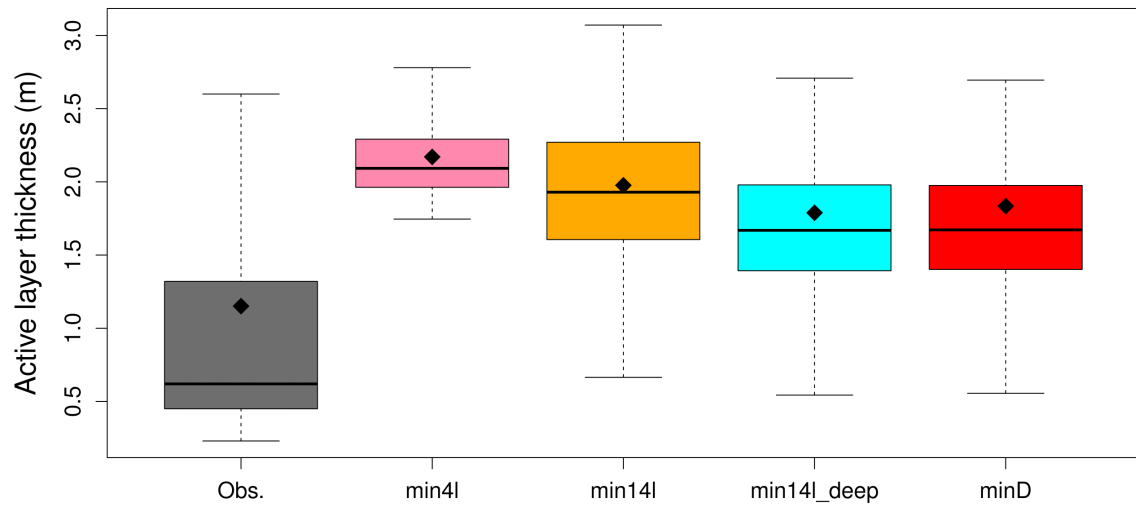


Figure 3: comparing with a new simulation (*min14l\_deep*) where bedrock starts at 3m

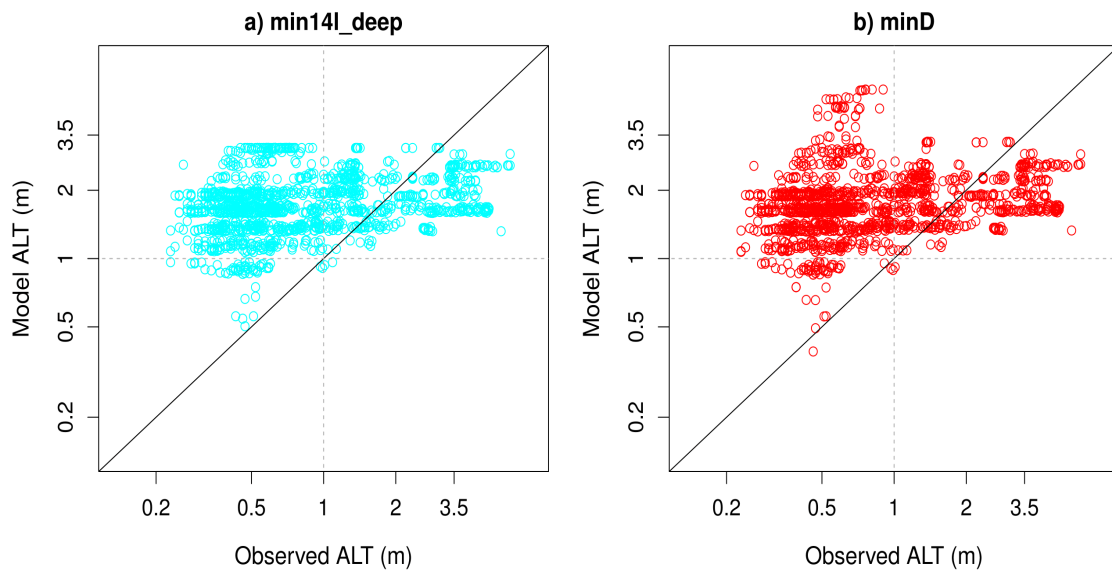


Figure 4: as Figure 3.