

Interactive comment on “An improved representation of physical permafrost dynamics in the JULES land surface model” by S. Chadburn et al.

S. Chadburn et al.

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We thank the referee very much for her/his comments. We answer the points in the order of the review and we have given a response for every point which we believe will be satisfactory. Please find below our response and updated text/figures.

Providing the data as a package for other modellers: Thanks for this suggestion! It is a great idea and something we would like to do. We are working on it.

1. In order to see how the model behaves across different ecosystems and locations we have performed large-scale model simulations. We have then compared these simulations with available observations, to see whether the model captures the overall

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patterns of soil temperature and thaw depth. We see that it is able to do this a lot better with the model improvements. The results from these simulations can be found in the following discussion paper: <http://www.the-cryosphere-discuss.net/9/1965/2015>. The observations with which we compare cover wide areas including discontinuous permafrost.

2. Where I defined active layer thickness as ‘maximum depth of summer thaw’, I have changed this in the text to ‘thickness of seasonally frozen layer’.

3. Yes, the moss layer has constant thickness for the large-scale case, although in future work we may allow it to change, at present we do not have data to evaluate large-scale patterns of moss thickness.

4. For the large-scale case we do have a non-constant fractional cover. The percentage of moss cover depends on a ‘health’ variable which is updated once a day depending on how good the conditions are for moss growth. The fraction also depends on the land cover as we limit the percentage cover to a certain fraction of the grid box depending on what else is present. To evaluate we compare with land cover maps. All the details of this are found in the large scale paper (see point 1, above, for URL).

5. I agree this could be confusing. I have re-structured as follows: Section 2.2.5 is moved to come immediately before section about bedrock, and the following paragraph is added: “In this last case, soil column depth is increased even further by adding an extra column to the base of the hydrologically active column, to represent bedrock. This bedrock column adds another 50 m, bringing the total soil column to 60 m. See [Section \ref{sec:bedrock}](#) for details.”

6. Firstly, the suggestion to move the part about snow density from Section 2.3.2 (‘Soil and land cover characteristics’) to Section 2.2.4 (‘Improved snow scheme’). The choice of snow density parameter is really based on site-specific information and is not a generic improvement to JULES. The sections are organised as follows 2.2: Describes model developments, 2.3: Describes site-specific parameterisation, thus I think the

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paragraph on snow density should remain in Section 2.3 as it is site-specific. To answer the second point, the calculation of changes in snow density is found in Best et al. (2011), equation (21), and I have added a reference to this in the text.

7. I agree that *std* is a confusing label. I have changed this to 'min4l' (meaning mineral, 4 layers), which is also consistent with the large-scale simulations in the second paper. I can't think of a much better way to do the rest of the labels, without making them very long. I hope you agree. The second reviewer also commented on 'std' but was happy with the others. I have changed this throughout the plots/text.

8. Is $\theta_u + \theta_f$ always equal to 1? θ_u and θ_f are the unfrozen and frozen water contents as a fraction of saturation, therefore they only add to 1 when the soil is saturated. Otherwise there would be no need to divide by this sum in equation 5! It is misleading that I have described θ_u and θ_f as unfrozen and frozen water 'fraction', so I have made this clearer in the text. "i" is a dummy variable in the sum over layers. "n+1" is the first frozen layer. I don't think a table could add much to the equation.

Updated text: "In this paper, the ALT is calculated by taking the unfrozen water fraction in the deepest layer that has begun to thaw, and assuming that this same fraction of the soil layer has thawed. This is represented by the following equation: ... where θ_f and θ_u are frozen and unfrozen water content as a fraction of saturation, and n is the deepest layer that has completely thawed ($\theta_{f,i} = 0$, for $i = 1, \dots, n$)."

9. I have re-written the conclusion following your suggestions, the new text is as follows: "Improvements have been made to the physical representation of permafrost in the JULES land-surface model. Additional processes represented include an insulating moss layer, the physical properties of organic soil, and a bedrock column. In addition, the representation of snow and discretization of the soil have been modified.

These developments are extremely relevant for the Arctic in general, since soils in the continuous permafrost zone are often organic-rich and covered by moss, which is certainly the case at Samoylov Island, where we run the model simulations. It is

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therefore important to include these processes in global land-surface models.

In the simulations, soil temperatures and active layer thickness (ALT) are significantly improved by the model developments. Firstly, increasing the model depth and resolution is necessary to correctly simulate the physical processes. It has been shown that a shallow soil column cannot give realistic permafrost dynamics, see eg. \cite{lawrenceetal2008}, and a high enough resolution is required to correctly solve the physical equations. Once this basic function of the model has been improved, including the new, permafrost-relevant processes of organic soils and moss leads to a great improvement in summer soil temperatures. The RMSE in summer soil temperatures decreases from 4.0°C to 0.7°C, and the ALT reduces by 0.7 m to fall within 0.1 m of the observations. This suggests that the most important processes for the summer have been included.

In the shoulder seasons, the zero-curtain duration is strongly related to soil moisture. This requires further work in JULES, as the model does not obtain the saturated conditions observed in the field. The relevance of this is seen by fixing the soil moisture in the 'saturated' simulation, which alters the timing of freeze-up from 30 days to only 13 days too early.

Snow is the most important process for winter soil temperatures, which can be seen here by the high correlation (0.85) between soil temperature error and snow depth error in the winter months. Soil temperatures are particularly sensitive to shallow snow, hence our improvement to the snow model is essential for simulating soil temperatures in the shoulder seasons. The snow on Samoylov Island is shallow and highly wind-blown, which is typical of these low-lying tundra regions. We find that the fresh snow density required to obtain the correct mid-winter snow density in JULES is too high, indicating a need for further work, potentially to include more snow compaction processes.

Another area for future development is the vegetation, since there are currently no

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specific high-latitude PFT's in JULES. The moss cover represented here is a first step towards simulating tundra vegetation, however this represents only the physical effects of a constant layer of moss, leaving more work to be done, for example on growth, carbon cycling, and on other types of vegetation.

We believe that we have significantly improved the representation of permafrost processes in JULES, providing generic model improvements that could be adopted in other GCM land-surface schemes. However, this is still a work in progress for the whole community. Even if a model simulates the right processes in a 1D column, scaling these up to represent sub-grid heterogeneity in a large grid-box is still an open problem \citep{musteretal2012,langeretal2013}. In most global land-surface models, only vertical processes are simulated, meaning the lateral flow of heat and water, and blowing snow are all omitted. Techniques to include these processes are currently under development \citep[e.g.,][tianetal2012,esserypomeroy2004,yietal2014]. Of course on the large scale, models are still heavily constrained by the availability and uncertainty of observational data.”

Figures: Thanks for the comment. I have changed Figure 6a to discrete colours, and the zero-degree isotherm is now quite clear (see attached file for new version of this figure). I have put in “Temperature, °C” on the legend for this plot, as indeed this was missing. For the legends on Figure 5 and 6b, listing which line belongs to which simulation, the labels are described in the figure captions and there is not space on the plot itself for more text.

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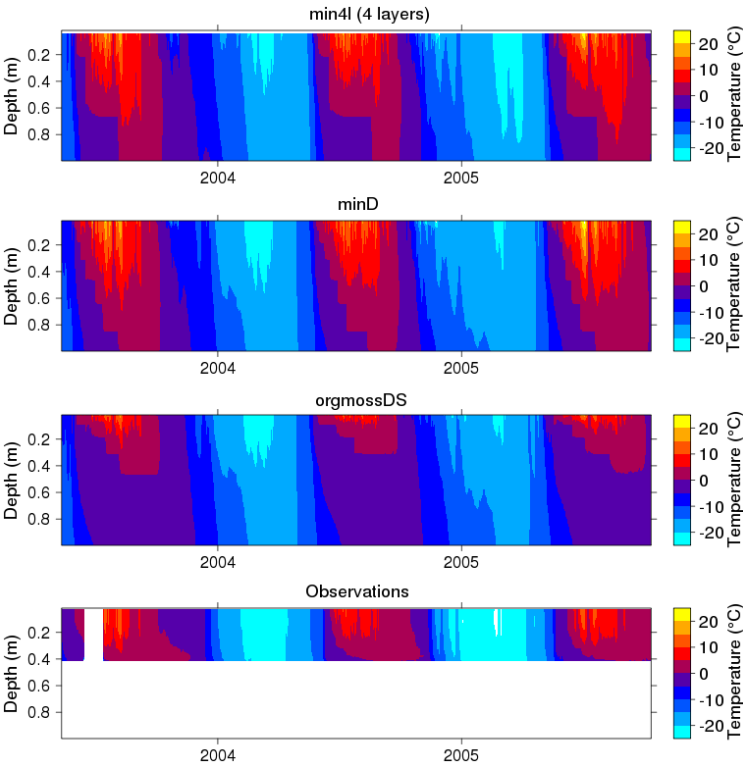


Fig. 1. New version of Figure 6a

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