Response to comments of reviewer 2

Before replying to the individual comments, we would like to sincerely thank the reviewer for the time and effort she/he has taken to review our submission. We hope that we managed to make good use of all suggestions and think that especially the (brief) discussion of the seasonality of effects has improved the quality of our manuscript.

Please note that, in the following point by point address, we repeat the reviewer's comments in red letters while our response is given in black letters. All the post-reply updates are indicated in blue.

The study "Representation of soil hydrology in permafrost regions may explain large part of inter-model spread in simulated Arctic and subarctic climate" by de Vrese et al. evaluates the impact of model settings influencing the hydrology in boreal and Arctic regions in the land surface model JSBACH. The purpose of the study is mainly to showcase the significant consequences of these settings on the simulated regional and even global climate, not so much to present new ways to resolve these shortcomings. But that is to be expected, given the magnitude of the problem.

The study follows a logic setup and the results are of great interest to the readers of TC. The manuscript is well written and I recommend publication after addressing the following points:

Major comment:

The authors focus the results on annual averages, but in most cases do not present the seasonality, which is important for understanding the changes. Two concrete examples in the following, but this aspect should be taken into account more throughout the entire manuscript:

In general, we would prefer to stick to showing and discussing the annual means as much as possible, as we think that the main findings and the general message of the manuscript do not require the additional detail. However, there are two important exceptions, where we agree with the reviewer that details with respect to the seasonal variability are indeed crucial. On one hand, low clouds affect the surface energy balance differently during summer than during winter. Thus, it is important to point out that the differences in the soil hydrology have an effect on the cloud cover mainly during spring and summer. On the other hand, the seasonal variability of the temperature differences clearly shows that the differences in soil hydrology can not explain the large ensemble spread during the snow covered period. Here, we think that these to points can be made using the examples provided by the reviewer.

L. 449 ff: This is a really important paragraph which should be extended by presenting the seasonality of the effects. As an example, 0.2mm per day corresponds to about 70mm per year, but I guess this difference will mostly accumulate in summer and fall when most of the evaporation occurs? Are there differences in the snowfall which could possibly affect the insulation of the snowpack and thus ground temperatures? Same for the cloud feeback, total incoming radiation (short- plus long-wave) should generally reduce for cloudy skies in summer, but increase in winter. So when is cloudiness increased, all year or mainly in summer?

While there are differences in the simulated snowfall and -cover, the most important factor is the seasonality of the differences in cloudiness. The cloud radiative effect is very different between the summer and winter cloud cover, hence, we agree that it is important to mention that the additional evapotranspiration in WET leads to an increased cloudiness almost exclusively during spring and summer (line 460 of the revised manuscript):

Furthermore, the differences in relative humidity result in differences in the cloud cover which constitute another important feedback on the surface energy balance (Fig. 6e). The increased cloudiness in WET occurs mainly during the snow free period – spring to early fall in the southern permafrost regions, with the length of the period decreasing in northward direction – when the surface reflectivity is determined by a comparatively dark vegetation cover and similarly dark bare soil areas. Thus, the more extensive cloud cover notably raises the planetary albedo (relative to DRY), reducing the surface incoming solar radiation by between 10 W m^{-2} at the beginning and 13 W m^{-2} at the end of the 21st century.

L. 519 ff: same here, would be really nice to present the seasonality of the effects. The authors emphasize the importance of permafrost many times, and the winter aspect, especially the snow cover, is highly important for permafrost occurrence and thaw.

We now include Fig. 8 (see below), showing the seasonality of the WET-DRY differences and the CMIP6 ensemble spread. For evapotranspiration and precipitation the WET-DRY differences and the ensemble spread are reasonably well correlated. However this is not the case for the surface temperatures, indicating that there are additional factors – most likely differnces in the parametrization of the snow cover – determining the peak in the ensemble spread. This we now discuss together with the results based on the annual mean values (line 508 of the revised manuscript):

In the case of precipitation, the differences in the soil-hydrology parametrizations appear to offer a large explanatory potential (Fig. 7b). On average $\Delta^{pr}_{|DRY-WET|}$ amounts to about 0.16 mm day^{-1}, IQR^{pr} to about 0.19 mm day^{-1} and $\pm\sigma^{pr}$ to 0.32 mm day^{-1}. Thus, even if considering $\pm\sigma^{pr}$ to be the more appropriate measure, about half of of the inter-model spread of

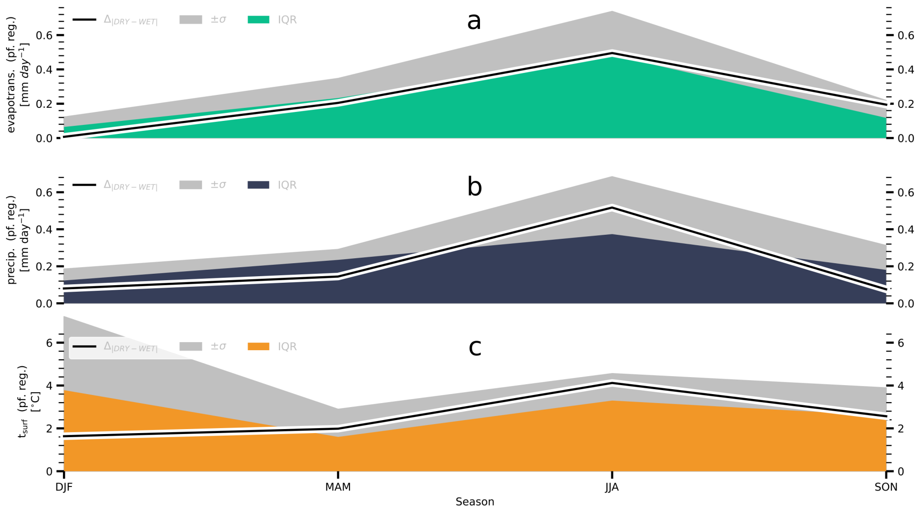

Figure 8. Comparison to CMIP6 ensemble – seasonality:

a) Simulated differences in evapotranspiration in permafrost regions and the respective CMIP6 ensemble spread. The black line shows the differences between WET and the DRY ($\Delta^{evap}_{|DRY-WET|}$), the green area gives the interquartile range (IQR^{evap}) — that is the difference between the 75$^{\text{th}}$ and the 25$^{\text{th}}$ percentile — of the CMIP6 ensemble, while the grey area provides 2 $\times$ the ensemble standard deviation ($\pm\sigma^{evap}$). b) same as a but for precipitation ($\Delta^{pr}_{|DRY-WET|}$, IQR^{pr}, $\pm\sigma^{pr}$), c) surface temperatures in permafrost grid cells ($\Delta^{ts}_{|DRY-WET|}$, IQR^{ts}, $\pm\sigma^{ts}$). Shown is the seasonality averaged over the 21$^{\text{st}}$ century.

the CMIP6 ensemble may be explainable by diverging evapotranspiration rates resulting from differences in the parametrizations of the permafrost hydrology. Here, $\Delta^{pr}_{|DRY-WET|}$ exhibits a marked peak in the summer months, when the causative differences in evapotranspiration are largest $\Delta^{evap}_{|DRY-WET|}$ (Fig. 8a,b). A similar behaviour can be seen for the ensemble spread, even though the (relative) seasonal variations are less pronounced, especially in case of IQR^{pr}. With regards to the surface temperatures, $\Delta^{ts}_{|DRY-WET|}$ matches the overall magnitude of the CMIP6 ensemble spread similarly well (Fig. 7c), with $\Delta^{ts}_{|DRY-WET|}$ being equal to IQR^{ts} (2.6 °C) and representing about two thirds of $\pm\sigma^{ts}$ (3.7 °C). However, as with the differences in precipitation, $\Delta^{ts}_{|DRY-WET|}$ peaks – at 4.2 °C – when the differences in evapotranspiration are largest (Fig. 8c), which is not the case for IQR^{ts} and $\pm\sigma^{ts}$. While the latter exhibit a notable increase in summer, their annual maximum occurs during winter – with 3.8 °C and 7.2 °C respectively – when $\Delta^{ts}_{|DRY-WET|}$ is the lowest. As described above (Sec. 3.1), the differences between WET and DRY mainly originate from a divergence of the cloud cover and the resulting differences in the planetary albedo. But as there are only minor differences in cloudiness – and very little solar radiation – during the snow cover season, this feedback is not present during the winter months. More importantly, the cloud radiative effect differs between the snow covered and the snow free period. The albedo of clouds is similar to those of snow and ice covered surfaces and an increase in cloudiness does not lower the planetary albedo in winter. Instead, (low) clouds are more likely to increase the surface temperatures as they raise the surface net radiation by reflecting the longwave radiation emitted by the surface (Vihma et al., 2016). Thus, it is mainly the differences in soil heat content – resulting from differences in the energy uptake *during the snow free period – and differences in latitudinal heat transport (not shown) that sustain* $\Delta^{ts}_{|DRY-WET|}$ *during winter, while it is most likely differences in the parametrization of the snow and ice albedo determining the large ensemble-spread (Menard et al., 2021). Consequently, the explanatory power of the differences in the soil-hydrology parametrizations appears to be limited to the snow free period.*

Minor comments:

-Introduction: there are very relevant model studies on paleoclimate that should be cited, e.g. Renssen, H., Isarin, R. F. B., Vandenberghe, J., Lautenschlager, M., & Schlese, U. (2000). Permafrost as a critical factor in paleoclimate modelling: the Younger Dryas case in Europe. Earth and Planetary Science Letters, 176(1), 1-5.

It is true that the representation of the permafrost related physics has most certainly had an impact on our ability to simulate the climate since LGM. However, as our investigation focusus exclusively on present-day conditions and the scenario period, we would prefer not to make the digression into the field of paleoclimatic modelling.

-Sect. 2.2 Why is the W2D setup not presented here?

We agree that the methods section is the better place to introduce the W2D setup and moved the description accordingly (line 325 of the revised manuscript):

"Although the manuscript focuses on the two setups described above, we performed a third, highly synthetic setup — the W2D setup – which exhibits increasingly dry conditions under a future warming. This setup assumes that the characteristics of the soil hydrology are determined by the presence of near-surface permafrost and change when the latter is degraded. All grid cells start with the parametrizations of the WET setup and the configuration is maintained as long as the model simulates permafrost in the upper 3 m of the soil. However, the parametrizations switch from WET to DRY (with the exception of the soil depths and the maximum wetland retention P_{lag}*) whenever the annual maximum thaw depth in the grid-cell extends beyond a depth of 3 m. For the high-emission scenario considered in this study, the majority of the grid cells in the northern permafrost regions transitions from WET to DRY during the 21*st *century, with the W2D simulation becoming increasingly different from the WET simulation."*

-L. 251 ff, "supercooled water": this implementation seems weird, the increasing ice content should simply decrease the hydraulic conductivity, thus limiting and finally suppressing both vertical and lateral flow? I agree that setting water mobility to zero for temperatures below the freezing point is better than allowing free flow as in unfrozen soils, but making the hydraulic conductivity dependent on water/ice content should be really straight-forward solution.

Indeed this is also what we expected when we build the model. However, we had to find out that in some regions a power-law-based ice impedance factor alone may be insufficient. We do apply such a factor to percolation and lateral drainage in the WET simulation (in DRY only to percolation). However, in clay rich soils a large fraction of the water may remain liquid when temperatures are below but close to the melting point. In this constellation an ice impedance factor substantially reduces but does not completely stop all movement of water. Consequently – though a very slow process – the soils can loose up to 20% of the soil water during winter. Thus, obtaining highly saturated soils with a perched water table with our model required to immobilize the supercooled water, which was actually done by including the supercooled water (essentially as extra ice) in the calculation of the ice-impedance factor (line 271 of the revised manuscript).

"In the implementation of Ekici et al. the supercooled water behaves similarly to water at temperatures above 0°C — that is, it can percolate through and drain from the soil. In the present version, the movement of supercooled water can be limited in the presence of ice, using the above described ice-impedance factors. However, some water movement, is still possible and especially clay-rich soils can loose a large fraction of the supercooled water over longer periods. To prevent this cold season drying of the soils from happening, we additionally included the option to "immobilize" the supercooled water, essentially prohibiting all fluxes below the freezing point."

-Fig. 8: My opinion, but I think the figure would be easier to read if the authors selected a more "traditional" design. Since the graphs are labelled a,b,c,d anyway, they could for example distinguish the individual bars in each plot by colors, but re-use the same colors in all plots.

Here, we (partly) followed the reviewers advice and re-use the same colors in the individual subplots (Fig. 9). However, as we would prefer to retain the same color-scheme as in Fig. 7 and 8, we show the bars of IQR in the color of the respective variables, i.e. green for evapotranspiration, blue for precipitation and yellow for surface temperatures. Please also note that, following the suggestions of reviewer 1, we restructured the manuscript and introduced a dedicated results section for the impacts outside of the terrestrial permafrost regions. Consequently, the differences in the region north of 50°N are no longer included in this figure – i.e. we removed panel d.

-Fig. 10 i: explain the grey area in the caption

In the figure caption (to now figure 12), we clarify that:

"In panel a - f and h, areas where differences are not significant (p-value > 0.05) are hatched, while subfigure g shows the minimum 3-year mean precipitation over land during the 50 year period without test of significance. Dark grey areas in panel i show the bathymetry of the Atlantic ocean."

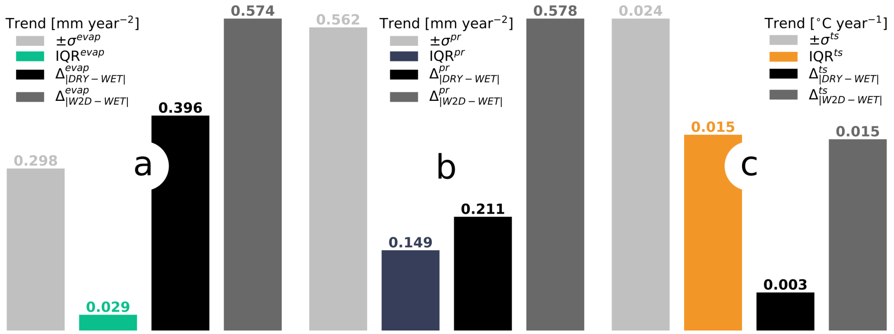

Figure 9. **Comparison to CMIP6 ensemble – 21st-century trends:**
a) Trends in evapotranspiration during the 21st century: 2 × the CMIP6 ensemble standard deviation, the interquartile range of the CMIP6 ensemble, differences between WET and DRY and differences between W2D and WET — averaged over the northern permafrost regions. b) Same as a) but for precipitation and c) surface temperatures.

References

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