Firn changes at Colle Gnifetti revealed with a high-resolution process-based physical model approach

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Response to reviewer 3 (Anonymous)

In this study, the authors present a coupled energy balance and firn model and compare the model's output to a large dataset of firn temperature records, as well as one firn core record of refrozen melt, at Colle Gnifetti. The authors quantified the increase in firn temperature as well as surface melt totals in this location over the period of 2003-2018. Improving surface energy and firn models is an important pursuit, especially under a warming climate scenario and the uncertainties in firn meltwater retention capabilities.
This is a nicely organized and clearly written manuscript. Additionally, the figures are logically organized and easy to interpret (with a few minor suggestions for improvement below). Please find my general and line-specific comments below.

We wish to thank the referee for the constructive and positive review. In the revised manuscript we are adopting all the suggestions, as detailed below. In this document, the review text is reported in *black italic*, while our responses are in blue. Updated figures are shown at the end of the document.

General comments:

Throughout the Discussion section, there were many mentions of imprecise comparisons and statements of significance without any quantification. The Discussion would be improved by the incorporation of values that justify statements of significant changes, variability, and appearances of correlation.

In the revised manuscript, we are adding quantification throughout the Discussion section. Specifically, we are adding numerical values to our statements of lines 307, 321 and 390, as well as to the caption of Fig. 6. Additional quantification will be provided in the Results section.

Further explanation of how the authors calculated the amount of refrozen melt was present in the unifr-2019 firn core would be helpful. How were the 31 cm of refrozen layers in the core, which certainly contained a mixture of ice and firn layers, converted to m w.e.?

The original manuscript reported the observed total ice content of the core (31 cm), without an estimation the corresponding refrozen amount. We are now making this section more informative by computing an adjusted estimate (14 cm w.e.) for the amount of refrozen ice in the core. We have computed the correction from the mean density of the ice-free core sections. We acknowledge that this computation involves a fair deal of uncertainty, due to the high variability of the density profile even in the ice-free core sections, and also due to the presence of "icy firn" which did not form well-defined ice layers. In the revised manuscript we update the discussion in both Sect. 5.3 and the Appendix.

The study highlights that there are still many unknowns with respect to predicting the depth of refreezing meltwater in a firn column. The authors mention that the percolation routine for the EBFM needs to account for the firn density and stratigraphy in order to improve the estimates of z_lim. Additionally, the microstructure of firn layers as well as the permeability of both undisturbed firn layers and those containing refrozen meltwater will be important for accurately estimating these depths of percolation.

We fully agree with this statement. In the revised manuscript we are adding a sensitivity study of the percolation parameter z_{lim}, showing a strong dependence of firn temperatures on the choice of its value. Thus, refining the percolation routine can be a future improvement for the EBFM simulation of cold firn.

Figure 1:
- The '(a)' and '(b)' labels in the two panels of the figure are hard to notice. Consider enlarging the labels or bolding the font.

Done.

- The legend symbol for the model cells is confusing because it's the same color as only one of the sites (SK). Perhaps make the legend symbol a neutral color to make it clearer that you're referring to all of the square boxes in the figure.

Done.

- It's not clear how the areas depicted in the two panels overlap. Consider adding a marker in panel (b) to designate where the CG study site is.

Done.

Figure 3:
- Which of the firn core sites in panel (a) is the KCC core site? Indicating this information would give more context to the results shown in panel (b) as well as areas of the text where KCC is mentioned.

The KCC core is now highlighted in Fig. 3.

Figure 6:
- The '(a)' and '(b)' labels in the two panels of the figure are hard to notice. Consider enlarging the labels or bolding the font.

Done.

Figure 8:
- It would be helpful to remind the reader of what the energy balance component acronyms stand for in the caption, especially 'SHF', 'LHF', and 'GHF' which are note explicitly defined in the text before this figure.

We agree, to solve this we are renaming all the energy balance components in the figure to match the notation of Eq. 1.

Line Specific Comments:
Line 27: 'Besides' instead of 'Beside'

Done.

Line 35: somewhat awkward transition here. What 'Then' is referring to is vague?

We agree, we are replacing it with "Thus".

Lines 48-49: is this the current range of firn temperatures, or the range measured in the 1976 campaign?

It is the range measured by Suter and Hoelzle (2002): their measurements are the most recent published results which include the south-facing slope in the North of the domain. We are rewording the sentence to make clear the source of the measurements.

Line 68: change 'on' to 'of' at the end of this line

Done.

Line 121: 'Besides' instead of 'Beside'

Done.

Lines 234-235: It's not immediately clear why the depth of 4 m in this study matches the firn temperatures of the CG saddle point at a depth of 20 m. What data was compared to determine the 4 m depth for z_lim?

In the revised manuscript we rewrite this section entirely, describing in detail the sub-surface model and the water percolation routine. We also clarify that the 20 m firn temperatures at the saddle point were measured by Haeberli and Funk (1991).

Line 314: remove 'in' after 'As such,'

Done. We are also substantially improving this section by removing the speculative interpretation of the dense, thick refrozen layers with limited refreezing capacity: a more convincing and verifiable explanation is based on thermal conductivity, which has a positive bias due to a bias in density induced by the fixed-depth percolation routine. In Appendix we are adding a sensitivity analysis showing the cooling effect of a positive thermal conductivity bias.

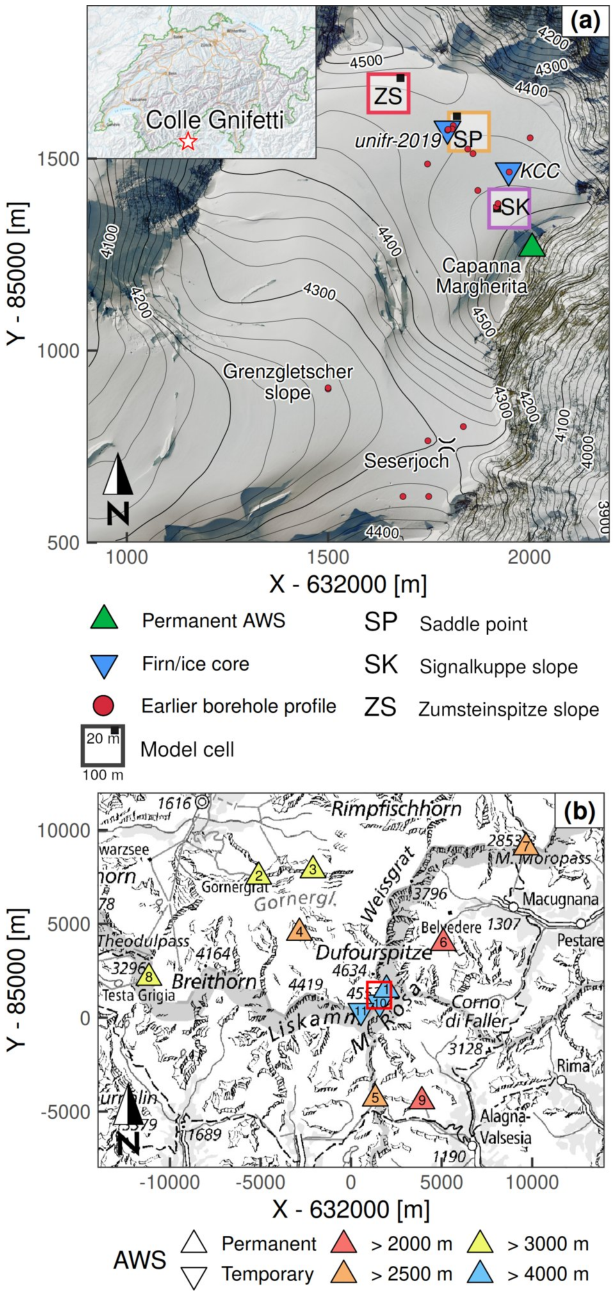
Line 322: should these units be °C yr-1?

Good catch, we are correcting the units.

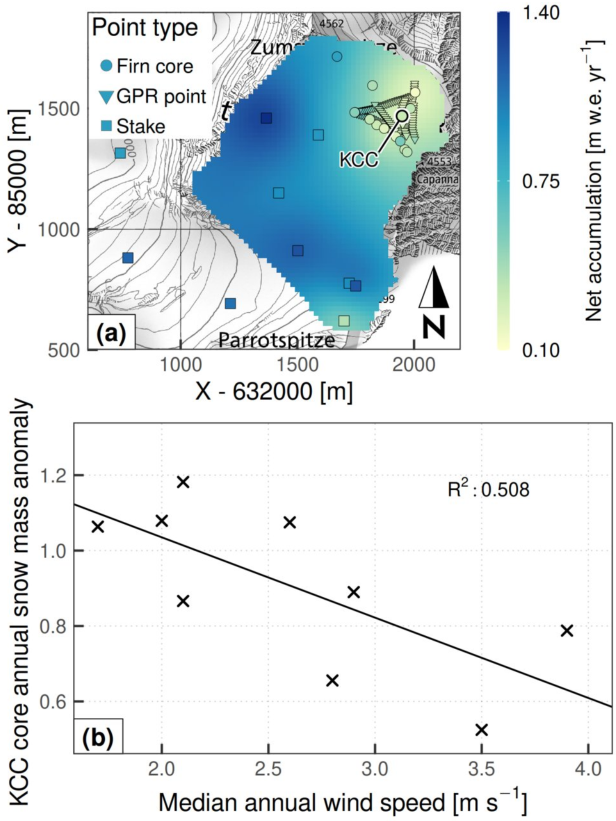
References

Haeberli W. and Funk M. (1991). Borehole temperatures at the Colle Gnifetti core-drilling site (Monte Rosa, Swiss Alps), *Journal of Glaciology* 37: 37–46.

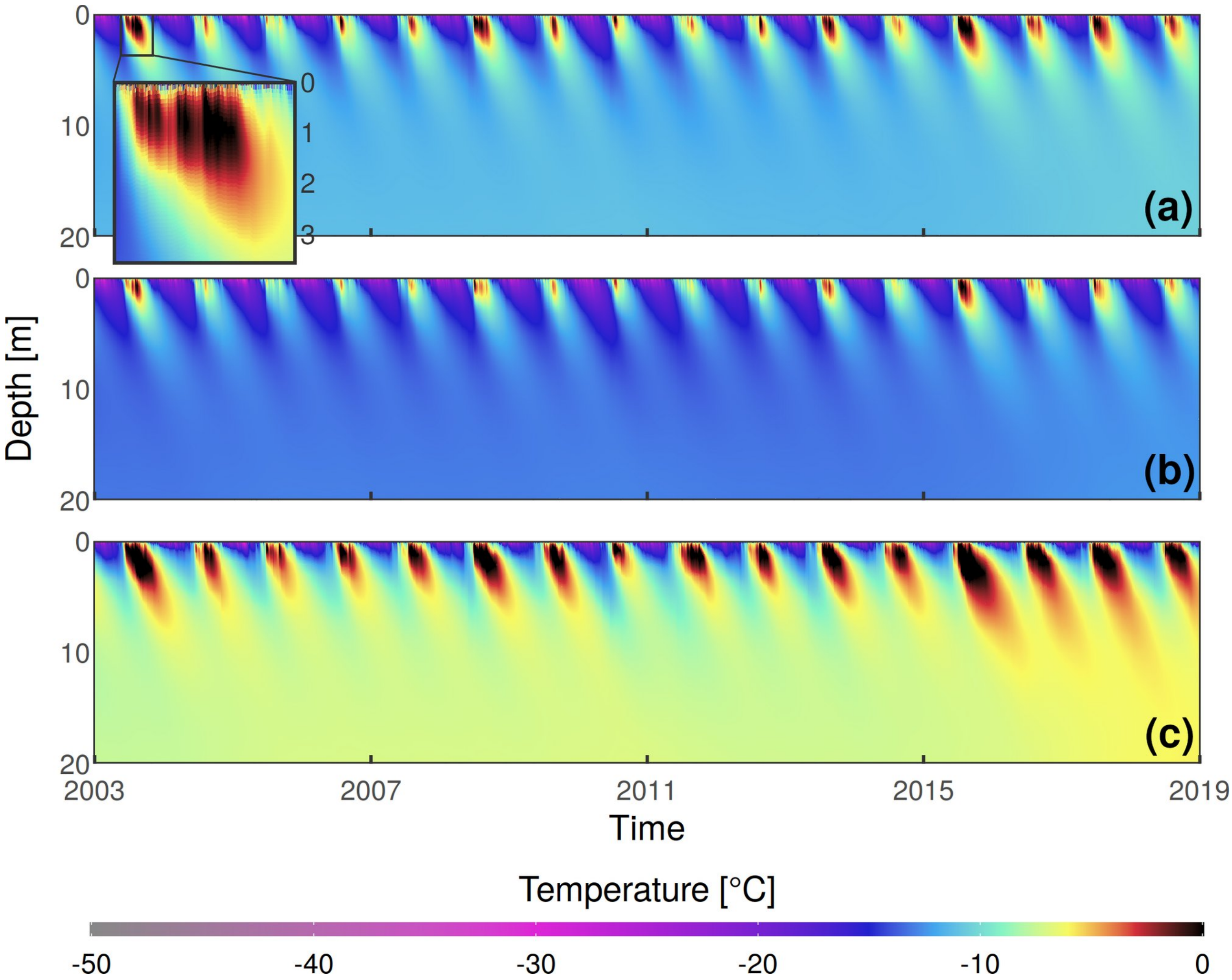
Suter S., and Hoelzle M. (2002). Cold firn in the Mont Blanc and Monte Rosa areas, European Alps: spatial distribution and statistical models. *Annals of Glaciology* 35: 9–18.



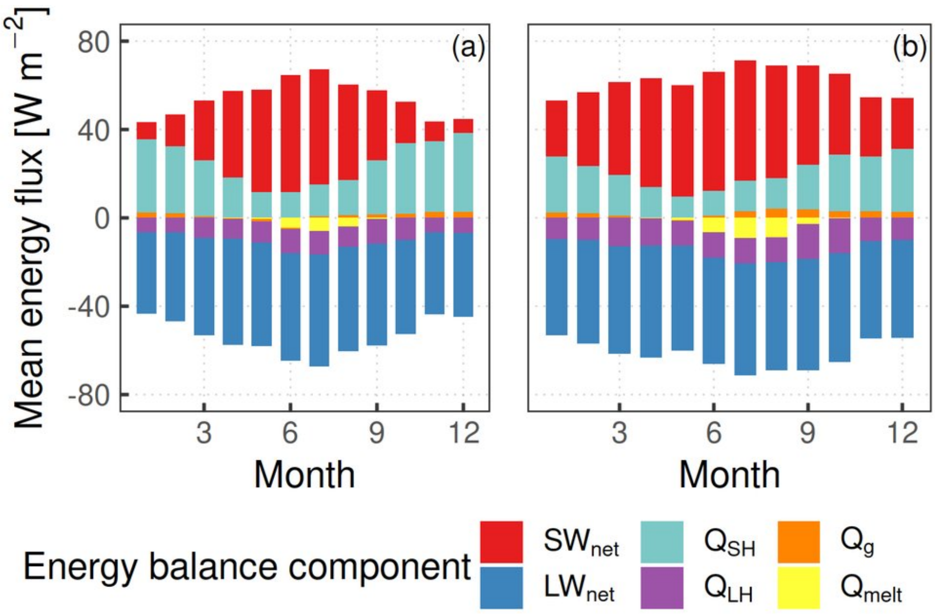
Updated Figure 1



Updated Figure 3



Updated Figure 6



Updated Figure 8