Firn changes at Colle Gnifetti revealed with a high-resolution process-based physical model approach
Enrico Mattea *et al.*

Response to reviewer 2 (Adrien Gilbert)

This paper is a modeling study of near-surface firn temperature evolution at Colle Gnifetti (Swiss Alps) between 2003 and 2018. The study uses a collection of unique meteorological dataset from high elevation to force a distributed surface energy balance coupled with a firn-pack model (Van Pelt et al., 2012). This study has the potential for an excellent scientific contribution regarding the quantification of thermal changes happening in cold accumulation area in response to atmospheric warming. I really appreciate the effort put by the authors in building the meteorological dataset based on an impressive amount of data to force their model. The use of a full surface energy balance associated with a representation of melt water percolation and refreezing allows to capture the firn temperature spatial pattern observed in the unique collection of temperature measurement realized at Colle Gnifetti over the last (almost) 20 years. The paper is also pretty well written and structured.

However, the manuscript suffers at this stage of incomplete or inadequate referencing to previous studies in the introduction and along the text and more importantly of the absence of sensitivity test regarding the subsurface model parameters. The consequence is that the discussion concerning model bias is not convincing and poorly supported. The parameters value of the sub-surface model as well as its mathematical description are absent which is critical for a paper focusing on firn temperature.

The manuscript therefore clearly needs major revision before publication. I hope to help to improve its weaknesses by highlighting the major points to revise in my general comments bellow and by providing a list of specific comments embedded in the attached PDF.

We wish to thank the referee for the thorough and constructive review, which is significantly helping to improve the quality of our manuscript. Below, we provide point-by-point answers to the referee's comments. The review text is reported in *black italic*, while our responses are in blue. Figures in this response are labeled with Roman numerals to distinguish them from figures in the manuscript.

General Comments

In the general introduction paragraph, the referencing to relevant studies in really poorly done (line 16 to 38). The same reference about the use of ice core archive is used multiple times when there is lot of other more relevant and specific studies. Please do a proper research in the literature. Also you cite Master degree thesis (inaccessible and not reviewed) when relevant published work exists. See my specific comments in the attached PDF.

In the revised manuscript we substantially improve the referencing, by citing specific, peer-reviewed studies relevant to the mentioned subjects. Later in this document we provide an extract of the introduction with updated references. We have opted to maintain some general references (e.g., Haeberli and Beniston, 1998, and Wagenbach *et al*., 2012) as we think they provide a general context relevant as background for our study. In particular, the Introduction section of Wagenbach *et al*. (2012) presents a detailed comparison of the characteristics of alpine ice cores in relationship to polar ones, as well as a comprehensive description of ice coring projects at both Colle Gnifetti and Col du Dôme. We will keep references to Master's degree theses only in relation to relevant work carried out at Colle Gnifetti within these theses, and not published elsewhere (specifically, the estimation of refreezing amounts done by Lier, 2018; a mention of the energy balance and firn model of Buri, 2013; and the reference to Mattea, 2020, for detailed information on the weather stations around Colle Gnifetti). The URLs to the full text of Buri (2013) and Mattea (2020), which are openly accessible, will be added to the References.

Also concerning past studies, you mostly ignored other studies done on the same topic and for very similar setup. I am probably oversensitive to it since it concerns my work but lot of the work done in Gilbert et al. 2014a and Gilbert et al. 2014b should be discussed and compared to your results. You will see many reference to it in my specific comments.

In the revised Discussion section we compare and discuss results from Gilbert *et al*. (2014a, 2014b).

The description of the sub-surface model should be included in the paper. There is no reason to describe the surface energy balance and not the energy transfer within the firn-pack. This is the essential part of the modeling and parameters are not even listen nor their value given.

Our motivation to describe the full surface model but not go into the sub-surface details was that we introduced significant changes to the surface model, compared to the version of van Pelt *et al*. (2019): we re-calibrated several parameters and we changed the accumulation model and the turbulent fluxes formulation. By contrast, we kept all sub-surface routines and parameters exactly as described in van Pelt *et al*. (2012) and Marchenko *et al*. (2017), except as detailed in Sect. 3.4. We understand that our choice could prove confusing to a reader not familiar with the model, and in the revised manuscript we are adding a description of the main sub-surface routines, as well as improved referencing to the studies which first introduced the sub-surface EBFM parametrizations. Specifically, we will present the following equations governing the evolution of layer temperature and density:

$$\rho_f c_p(T_f)\frac{\partial T_f}{\partial t}=\frac{\partial}{\partial z}\left(\kappa(\rho_f)\frac{\partial T_f}{\partial z}\right)+\frac{F L_m}{\Delta z} \quad (1)$$

$$\frac{\partial \rho_f}{\partial t}=K_g(\rho_f, T_f)+\frac{F}{\Delta z} \quad (2)$$

$$K_g(\rho_f, T)=b_{acc} \; g(\rho_{ice}-\rho_f)\exp\left(\frac{-E_c}{R T_f}+\frac{E_g}{R T_{avg}}\right) \; C_{Lig}(b_{acc}) \quad (3)$$

where ρ_f and T_f are layer density and temperature, c_p firn heat capacity, z depth, κ effective conductivity, F refreezing rate, L_M latent heat of melting, Δz layer thickness, K_g gravitational densification as in Arthern et al. (2010), b_{acc} accumulation rate in mm a^{-1}, ρ_{ice} ice density, R universal gas constant, E_c (60 kJ mol^{-1}) and E_g (42.4 kJ mol^{-1}) activation energies of creep by respectively lattice diffusion and grain growth, T_{avg} year-averaged firn temperature and C_{Lig} a correction based on the accumulation rate, accounting for different densification regimes above and below the critical density of 550 kg m^{-3} (Ligtenberg *et al.*, 2011; van Pelt *et al.*, 2012). We are also adding mention of the parametrizations for specific heat (Yen, 1981) and thermal conductivity (Sturm *et al.*, 1997). Furthermore, we show the explicit formulation for the irreducible water content (Schneider and Jansson, 2004):

$$\theta_{mi} \;=\; 0.0143\exp(3.3 n_p) \quad (4)$$

where n_p is porosity, and we add the formula of the preferential percolation routine (Marchenko *et al.*, 2017):

$$PDF(z, z_{\text{lim}}) \;=\; 2\frac{\exp\left(\frac{-z^2}{2\sigma^2}\right)}{\sigma\sqrt{2\pi}} \quad (5)$$

where z is depth, and σ standard deviation computed as $z_{lim}/3$, such that 99.7 % of the input water is distributed above z_{lim}.

From my understanding, you do not take vertical advection into account, the vertical advective heat transport can be significant in cold accumulation zone and should be taken into account. Also what are you doing with precipitation? It is not explained, maybe the vertical advective transport is actually taking into account? Since the subsurface model is not described, it is not clear. The only thing that makes me thinking you actually do, is the thickness of your active layer reaching 20m-depth which is possible only with advection. You need to clarify this in the manuscript.

We acknowledge that this was not clearly specified in the manuscript. Vertical advection is taken into account by the Lagrangian grid discretization (line 242): in the model, layers are free to move on the vertical axis (to prevent numerical diffusion), thus they carry their temperature signal to depth as they are buried by progressive accumulation. This also explains one purpose of precipitation/accumulation in the EBFM: it adds snow at the top of the grid, creating new layers and pushing the others down. Accumulation also appears in the densification formula (Eq. 3). In the revised manuscript we describe the sub-surface model, including an explanation of the moving layers mechanism and an explicit mention of advection.

The bigger weakness of the manuscript is the absence of sensitivity test concerning the sub-surface model parameters and their influence on the modeled firn temperature. You cannot discuss the model bias without it. For instance, discussing short wave radiation redistribution due to reflection in order to explain your bias is not convincing at all when many parameters modification could explain the biases. From my experience, cold biases in firn temperature model often arise from neglecting short wave radiation penetration. Gilbert et al. (2014a) show that a characteristic penetration length of 2.5 cm is able to significantly change the modeled firn temperature and explain the cold bias observed in their study site at 4250 m a.s.l. As you mention, warm bias could be explained by not accurate representation of water percolation and refreezing. I agree, but to be convincing, you have to perform sensitivity tests on the water percolation parameters and explicitly show the result of these tests. We don't even know what the real meaning of the percolation depth parameter is, since the model is not described. Also the residual saturation parameter due to capillarity force is a critical parameter which is not well constrained. I suggest to test its influence on your results, you could be able to correct your warm bias.

In the revised manuscript, we add an Appendix section presenting sensitivity of modeled firn temperatures to several surface and sub-surface parameters, based on reduced model runs (for performance reasons) including the three points of Fig. 1a. We also improve the discussion of the model temperature biases by referring to these computed sensitivities. Moreover, we are adding a full description of the percolation routine, explaining the meaning of the percolation depth parameter z_{lim} (see Eq. 5 above).
Firn temperatures are very sensitive to the value of the percolation depth parameter: a decrease from 4 to 2 m (Fig. Ia) produces a cooling by 1.5-4 °C, with a clear dependence on melt amounts. The largest change is at the high-accumulation, high-melt ZS location. A deeper value of z_{lim} = 6 m (Fig.

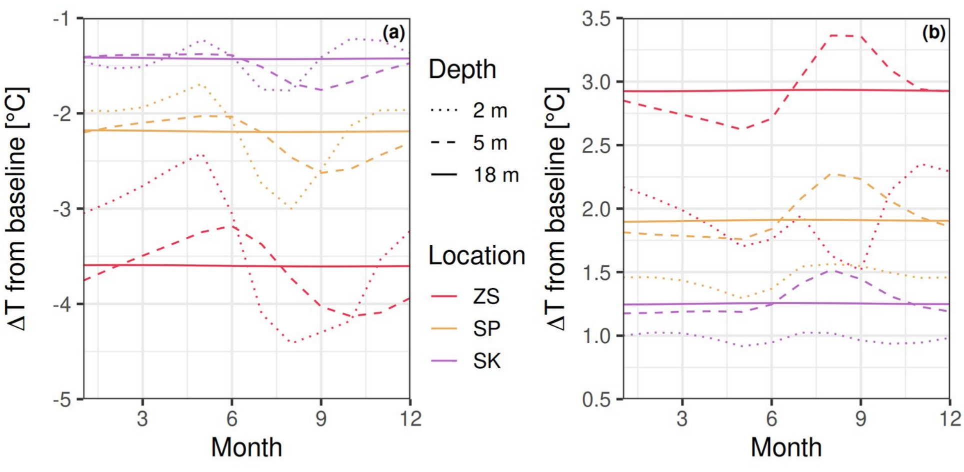

***Figure I:** firn temperature change by month, depth and location, resulting from a change of the percolation depth parameter z_{lim} from 4 m to **(a)** 2 m, **(b)** 6 m.*

Ib) increases firn temperatures by 1-3 °C. Due to this high sensitivity, especially at locations with high accumulation and melt rates, it would be an interesting topic for a future study to test and compare different water percolation routines at our site, such as gravity flow theory (Colbeck and Davidson, 1973) which has been successfully applied on cold firn by Gilbert *et al*. (2014b).
By contrast, sensitivity to the residual saturation (Fig. II) is almost negligible at the two low-melt locations of SP (saddle point, renamed from CG) and SK: this is likely due to the small meltwater amounts being distributed by the percolation routine over a vertical extent of 4 meters, such that all water can refreeze immediately and residual saturation does not play an important role. At the high-melt ZS location, residual saturation begins to show some small effects: firn temperatures increase by about 0.25 °C by halving the residual saturation compared to the baseline (Fig. IIa), and decrease by 0.1 °C with the opposite change (Fig. IIb). Thus, we would conclude that residual saturation is not the most critical parameter for calibration in the present Colle Gnifetti setup; still, this parameter would probably be more relevant when modeling scenarios of future evolution, which are expected to include more meltwater production.

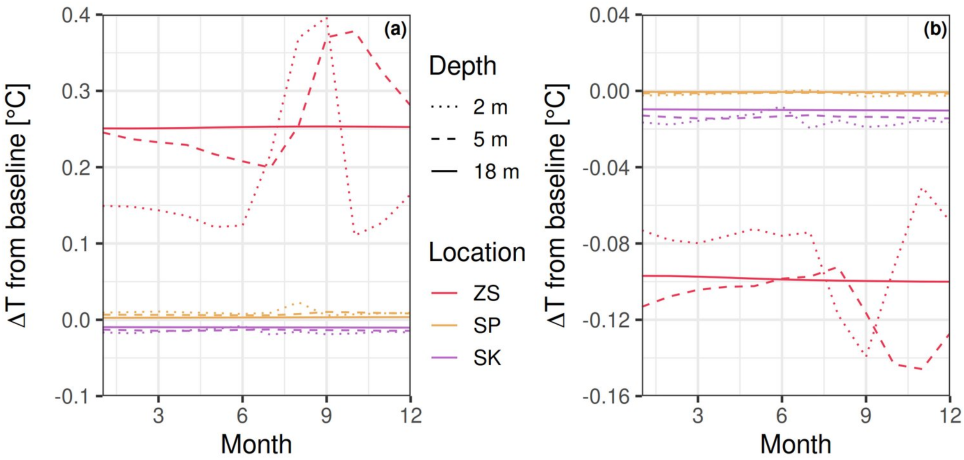

Figure II: *firn temperature change by month, depth and location, resulting from a change of residual saturation by a factor* ***(a)*** *0.5,* ***(b)*** *2, from the formula of Schneider and Jansson (2004).*

We have now quantified the effect of reflected radiation redistribution between Sun-exposed and shaded cells. For this, we have used a simple model of Lambert (isotropic) reflectance (e.g. Koppal, 2014), applied to our simulated series of 2003-2018 hourly reflected SW radiation over the model grid. Our estimations (Table I) for the three grid cells of Fig. 1a indicate that the magnitude of SW radiation redistribution is indeed negligible compared to the other energy fluxes. We are updating the text to reflect these findings.

Table I: *mean (2003-2018) simulated energy fluxes arising from SW radiation redistribution. The net difference between received radiation and intercepted outgoing radiation is the relevant metric towards the spatial distribution of temperature biases, because absolute received radiation alone could be easily compensated by albedo calibration.*

	ZS	**SP**	**SK**
Mean SW radiation received by a cell from the other grid cells [W m^{-2}]	2.19	0.62	0.68
Mean SW radiation outgoing from a cell and intercepted by other grid cells [W m^{-2}]	2.83	0.65	0.72
Net difference of the previous two [W m^{-2}]	-0.64	-0.03	-0.04
Net difference reduced by 80 % (mean albedo) [W m^{-2}]	-0.14	-0.01	-0.01

Incorporating SW radiation penetration in the EBFM (in an energy-conserving manner) is unfortunately not straightforward. This is because melt amounts would no longer be computed simply from the surface energy balance and surface temperatures. Penetration of SW radiation into the sub-surface implies that melt can happen inside the snow pack instead of originating entirely at the surface. In fact we would expect that a significant fraction of modeled melt would happen in the (shallow) sub-surface: the reason is that (with SW penetration) the energy balance of an infinitesimally thin surface layer will have in principle no incoming SW component (e.g., Kuipers Munneke *et al*., 2009), thus the SEB would rarely reach melting conditions. Simulation of this process would require a major restructuring of the model architecture, going beyond the scope of our study. Due to the relatively shallow penetration depths (e.g., Warren, 1982; Fukami *et al*., 1985), we anticipate that including the penetration of SW radiation would require significantly thinner near-surface layers in the model compared to our 5-10 cm layers. A realistic simulation of radiation penetration should also include the non-exponential decay of incoming flux close to the surface, due to non-uniform spectral extinction (Warren, 1982; Beaglehole *et al*., 1998). In the revised manuscript, we add a paragraph discussing the issue of radiation penetration, mentioning the process as a potential contributor to our aspect-dependent temperature bias.

What about the firn thermal conductivity? Recent work of Calonne et al. (2019) should be used. The author corrected a significant bias on the commonly used conductivity/density relationship.

In the revised manuscript we provide information on which parametrization of thermal conductivity is used in the EBFM (Sturm *et al*., 1997). We agree that the formula of Calonne *et al*. (2019) should become the norm in firn modeling. Due to the very high computational cost of performing a new full EBFM run (spin-up and actual simulation), we have opted to test the Calonne *et al*. (2019) parametrization within a reduced model run, consisting of the three model cells highlighted in Fig. 1a. These locations are representative of the varying conditions of accumulation and melt found across the CG saddle. In the reduced model run (still at 20 m resolution and 1 h time-step) we have applied the full-grid topographic shading routine to ensure consistency with the original “baseline” model result. We will provide the result in the new Appendix B, in terms of the sensitivity of firn temperatures to the change of parametrization. In the firn density range of interest at CG, the Calonne *et al.* (2019) formula increases conductivity by about 20-50 % compared to Sturm *et al*. (1997). As a result, deep firn temperatures decrease by 1-2.5 °C, with some more differences in the seasonal cycle at shallower depths (Fig. III). We interpret this cooling as the result of two factors: (1) melt amounts decrease (about 10 %) because the higher conductivity delays the onset of melt (larger heat loss towards the glacier when the SEB approaches melting conditions); (2) modeled near-surface temperatures are on average colder (by 3-4 °C) than deep temperatures, thus a higher conductivity shifts the deep equilibrium temperature towards colder values. In the revised manuscript we present this discussion of thermal conductivity; the Calonne *et al*. (2019) parametrization will also be included by default in an upcoming release of the EBFM.

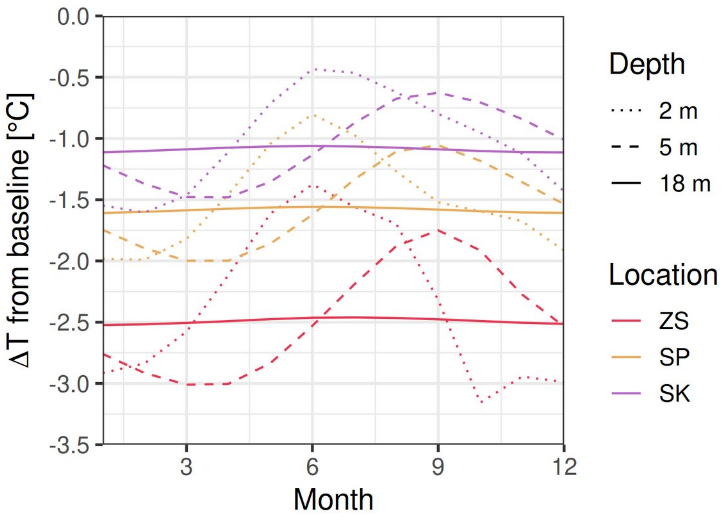

Figure III: *firn temperature change by month, depth and location, resulting from a change of the thermal conductivity parametrization from Sturm* et al. *(1997) to Calonne* et al. *(2019).*

My final general comment is about the presentation of the results. You have a really nice distributed model but you do not really use it to show the spatial heterogeneity of the firn warming which would be a valuable result. I suggest to add a map of current firn 20m-depth temperature and a map of the associated warming rate. You will see it in my specific comments in the attached pdf.

In the revised manuscript, we provide maps of current firn temperatures and 2003-2018 trends; they are also shown below (Fig. IV). The relative distribution of firn temperatures is consistent with the result of Suter and Hoelzle (2002), confirming the observed strong spatial gradient towards the western region of the domain. Warming rates have a relatively complex distribution, likely affected by the relative importance of incoming solar radiation and air temperature on the present-day firn temperatures. The slower warming rate in the near-temperate region matches the observations of Hoelzle *et al*. (2011).

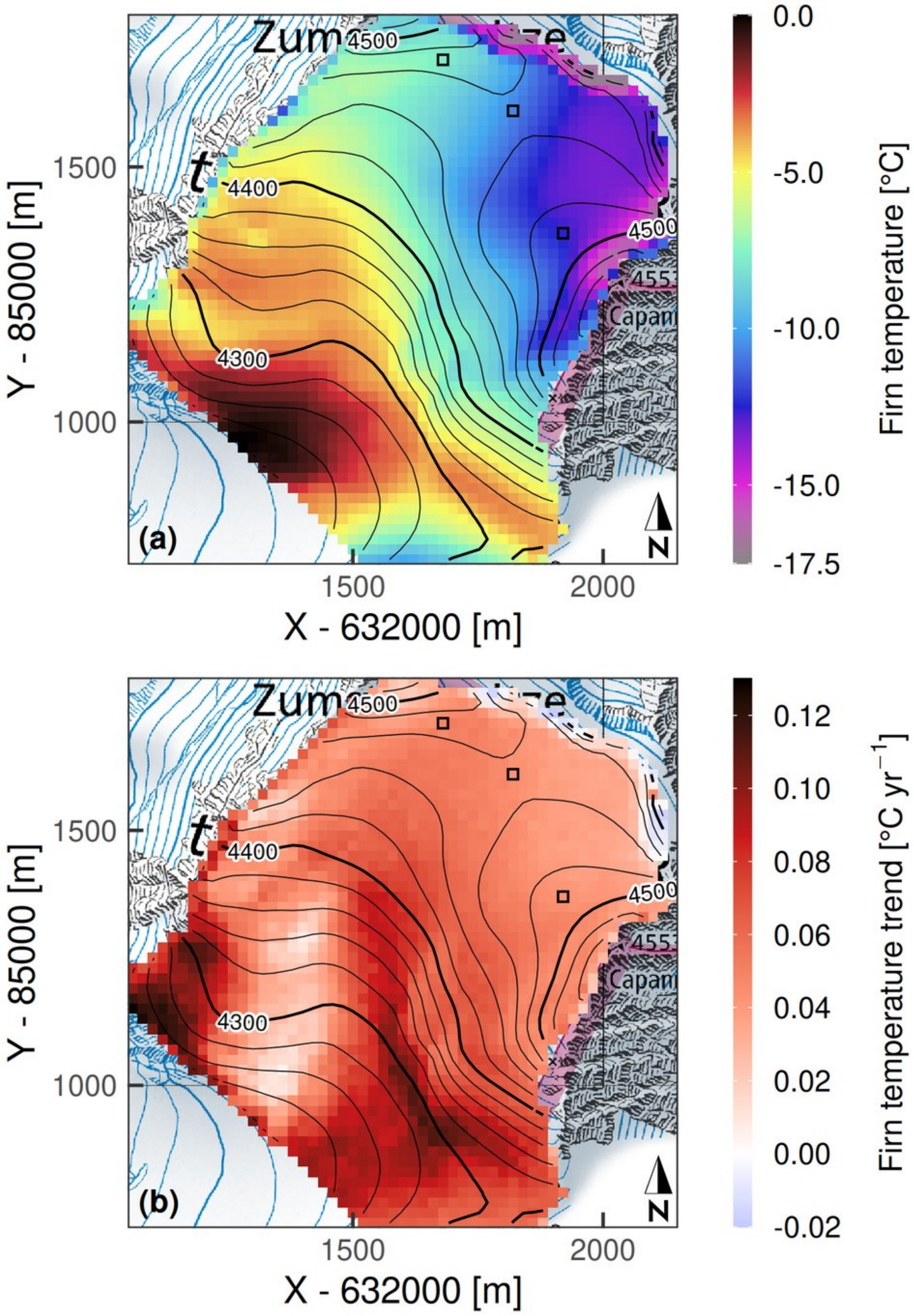

Figure IV:* (a)** *modeled 20 m firn temperatures at Colle Gnifetti on 31 December 2018;* ***(b) *modeled 20 m temperature trends over 2003-2018.*

Specific Comments

You will find a list of specific comments embedded in the attached pdf. They are sometimes redundant with my general comments but will help to clarify them.

In the revised manuscript we are implementing all the recommendations from the specific comments, except as noted below or (for repeated subjects) in the corresponding general comments.

lines 33-34

transition from cold to temperate do not necessarily mean mass loss, not very relevant I would just keep the degradation of the climatic archive.

This observation would appear to contradict the role of cold firn as a buffer against mass losses through refreezing. As stated in Vandecrux *et al*. (2020), *"The meltwater retention capacity of the firn depends on three physical characteristics: (i) the availability of pore space to host the meltwater, (ii) the availability of cold content to refreeze the meltwater and (iii) the possibility for meltwater to percolate in deeper firn where conditions (i) and (ii) are met"*. Transition from cold to temperate corresponds to the disappearance of characteristic (ii). For the CG setting, Hoelzle *et al.* (2011) state that *"As soon as all these areas become temperate, meltwater will be released in large quantities into the water cycle [...]"*.

Thus, we would keep the mention of mass loss, while improving the referencing within this section. We would also add mention of a third consequence of the cold-temperate transition, namely the possible destabilization of cold-based hanging glaciers (Gilbert *et al*., 2015).

line 63

What do you call "cold content" ? Surface accumulation control the vertical advection of the heat which influence the thickness of the active layer and the efficiency of the heat transfert toward the glacier base.

Here we used "cold content" as the amount of energy required to bring the snow cover temperature up to freezing (e.g., Vandecrux *et al*., 2020). As mentioned by Kuipers Munneke *et al*. (2014), *"the total refreezing capacity of the firn is ultimately determined by the total cold content provided by snowfall. This cold content is linearly proportional to the accumulation rate"*. We are adding the Kuipers Munneke *et al*. (2014) reference to the statement, together with an explicit mention of heat advection.

lines 65-66

It does not tell what complexity Suter is missing ? Mean snow accumulation is a good proxy of surface vertical velocity for steady state topography which roughly the case at Colle Gnifetti.

Good catch, our description of the Suter *et al*. (2001) model was wrong. As stated in that paper,
"The following assumptions and simplifications are made:

- *heat transfer is reduced to vertical heat conduction (vertical heat advection by surface accumulation, and corresponding downward motion of the snow and firn are neglected)*
- *latent heat (refreezing meltwater); convective heat transport by the air and liquid water; sensible heat; radiation; frictional heat by ice deformation; lateral firn and ice advection; and the ground heat flux are neglected*
- *the firn density is assumed to be constant with depth*
- *the air temperature at the surface equals the snow surface temperature (being the result of the surface energy balance) and follows a sine curve with a period of 1 year*
- *the monthly mean air temperatures are assigned to the 15th of each month."*

In the revised manuscript we provide the correct mention of missing heat advection.

lines 315-317

Not really convincing argumentation to explain the cold bias. For instance, neglecting short wave penetration through the snowpack (even of a few centimeter) strongly impact the firn temperature. A sensitivity study of the firn pack model parameter is really missing in the paper.

We agree that the argumentation here was mostly speculative and we are removing it from the revised manuscript. As mentioned above, we are also adding the new sensitivity results to the sub-surface parameters. In the discussion of the cold bias, we are adding a mention that radiation penetration could explain the bias, as reported by Gilbert *et al.* (2014b). We are also formulating another hypothesis for a process which could contribute to the cold bias, arising from the observations of sensitivity to thermal conductivity (Fig. III). Specifically, in the Discussion we had mentioned that repeated melt/refreeze cycles of the same surface could contribute to the discrepancy between modeled and observed melt amounts (Sect. 5.3). After each melt event, the percolation routine always distributes meltwater over the first 4 meters, even if melt amounts are small (the frequent micro-events of Fig. 10). As such, repeated melting is not accounted for (a new snow surface is melted each time in the model), and refreezing over the first 4 meters keeps increasing the firn density (see Eq. 2 above), especially at low-accumulation locations where the addition of new low-density layers is slow. This could result in a positive bias in modeled density, which would correspond to a positive bias in thermal conductivity: in turn, this would induce a cold bias, as shown above in the discussion about the Calonne *et al*. (2019) thermal conductivity. This explanation appears to be consistent with the observations of (1) cold bias mostly affecting the regions of very low accumulation/advection, and (2) reduced bias when accumulation (hence advection of low-density layers) is artificially increased (line 310). Indeed, even though our paper focuses on melt amounts and firn temperatures, a simple visual inspection of modeled firn densities revealed a positive bias at locations of low accumulation (Fig. Va), mostly disappearing at locations of high accumulation (Fig. Vb).

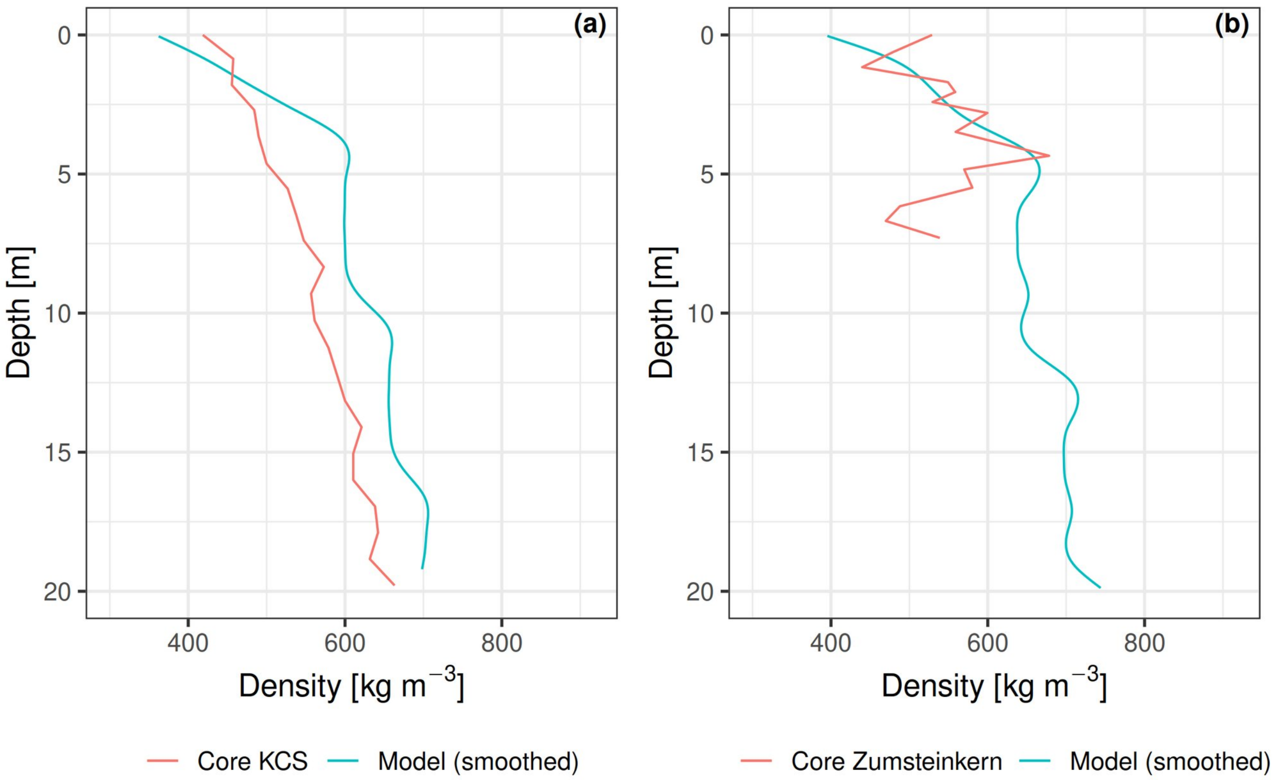

Figure V: *measured and modeled densities for* ***(a)*** *core KCS,* ***(b)*** *core Zumsteinkern. Deep core KCS is located close to the saddle point (4450 m a.s.l.) and has a mean annual accumulation of 0.51 m w.e. (Licciulli* et al.*, 2020). Shallow core Zumsteinkern is located at the south-facing ZS location (4470 m a.s.l.) and has a mean annual accumulation of 0.87 m w.e. (Lier, 2018).*

line 393
This is not a strong constrain validating your results...

We fully agree that this is not a validation of our results. If anything, our results are an example which corroborates the theoretical estimations of the cited paper. We feel that this reference is worth mentioning in a discussion about the conditions for melt initiation and melt occurrence at negative temperatures, which have not been examined very often in the literature. In the revised manuscript we reword the sentence to make it more neutral.

Updated Introduction (first section)

Cold firn and ice – defined by negative temperatures year-round – are recognized as a valuable archive of past atmospheric conditions, accessed through ice cores (e.g., Masson-Delmotte et al., 2006; Lüthi et al., 2008; Wolff et al., 2010; Wagenbach et al., 2012). In the recrystallization and recrystallization-infiltration firn facies, meltwater infiltration is respectively absent or limited to the near-surface layer of the firn (Shumskii, 1964; Hoelzle et al., 2011). This enables preservation of the original layering of accumulated snow, which can be dated to provide an atmospheric record including greenhouse gases, aerosols, precipitation, and isotopic temperature proxies (e.g., Preunkert et al., 2001; Barbante et al., 2004; Thevenon et al., 2009; Konrad et al., 2013; Bohleber et al., 2018).

The longest records are found in ice cores from the polar regions. Nonetheless, cold firn is also present in the Alps above 3400–4150 m a.s.l., depending on location and aspect (Suter et al., 2001). Such alpine cold firn is located close to major, historical sources of European anthropogenic emissions, thus providing a particularly valuable record of man-made changes to atmospheric composition (Jenk et al., 2006; Thevenon et al., 2009; Legrand et al., 2013). Moreover, the Alpine region features a historically high density of meteorological observations as well as other paleoclimatic records (such as tree rings and speleothems), enabling calibration and comparison of the atmospheric climatic archives (Wagenbach et al., 2012, and references therein).

Besides its importance for ice core studies, cold firn also acts as a buffer against glacier mass losses caused by a warming climate. Specifically, meltwater refreezing close to the surface does not contribute to water runoff: thus an increased input in the firn surface energy balance (SEB), with enhanced meltwater production, does not directly affect mass balance (e.g., Harper et al., 2012). As a result, rising temperatures – instead of mass losses – are the main expression of 20th-century atmospheric warming in cold firn (Gilbert and Vincent, 2013; Hoelzle et al., 2011; Vincent et al., 2020; Haeberli and Beniston, 1998).

Climate change is expected to trigger a progressive transition from cold to temperate firn, naturally advancing from the lower elevations towards the higher (Lüthi and Funk, 2001; Vincent et al., 2007; Gilbert et al., 2010). Expected consequences for sites of presently cold firn are the onset of mass loss (e.g., van Pelt and Kohler, 2015) and an irremediable degradation of the climatic archive, induced by meltwater infiltration to increasing depths (Gabrielli et al., 2010; Hoelzle et al., 2011). Moreover, a change in thermal regime could affect the stability of cold-based hanging glaciers, with potentially hazardous consequences (Gilbert et al., 2015). Thus, a better understanding of this transition will become crucial to the continued viability of ice core campaigns, as well as the mitigation of glacier hazards and the prediction of future runoff regimes in high-alpine and polar catchments. Particularly valuable will be the acquisition of quantitative modeling capabilities to estimate the timing and uncertainties of firn changes, also incorporating the regularly updated climatic scenarios.

References

Barbante C., Schwikowski M., Döring T., Gäggeler H. W., Schotterer U., Tobler L., Van de Velde K., Ferrari C., Cozzi G., Turetta A., Rosman K., Bolshov M., Capodaglio G., Cescon P., and Boutron C. (2004). Historical Record of European Emissions of Heavy Metals to the Atmosphere Since the 1650s from Alpine Snow/Ice Cores Drilled near Monte Rosa. *Environmental Science & Technology* 38(15): 4085–4090.

Beaglehole D., Ramanathan B., and Rumberg J. (1998). The UV to IR transmittance of Antarctic snow. *Journal of Geophysical Research: Atmospheres* 103(D8): 8849–8857.

Bohleber P., Erhardt T., Spaulding N., Hoffmann H., Fischer H., and Mayewski P. (2018). Temperature and mineral dust variability recorded in two low-accumulation Alpine ice cores over the last millennium. *Climate of the Past* 14(1): 21–37.

Calonne N., Milliancourt L., Burr A., Philip A., Martin C. L., Flin F., and Geindreau C. (2019). Thermal Conductivity of Snow, Firn, and Porous Ice From 3-D Image-Based Computations. *Geophysical Research Letters* 46: 11. doi:10.1029/ 2019GL085228

Colbeck, S. C. and Davidson, G.: Water percolation through homogenous snow, The Role of Snow and Ice in Hydrology, Proc. Banff. Symp., 1, 242–257, 1973.

Fukami H., Kojima K., and Aburakawa H. (1985). The Extinction and Absorption of Solar Radiation Within a Snow Cover. *Annals of Glaciology* 6: 118–122.

Gabrielli P., Carturan L., Gabrieli J., Dinale R., Krainer K., Hausmann H., Davis M., Zagorodnov V., Seppi R., Barbante C., Dalla Fontana G., and Thompson L. G. (2010). Atmospheric warming threatens the untapped glacial archive of Ortles mountain, South Tyrol. *Journal of Glaciology* 56(199): 843–853.

Gilbert A., and Vincent C. (2013). Atmospheric temperature changes over the 20 th century at very high elevations in the European Alps from englacial temperatures. *Geophysical Research Letters* 40(10): 2102–2108.

Gilbert A., Gagliardini O., Vincent C., and Wagnon P. (2014a). A 3-D thermal regime model suitable for cold accumulation zones of polythermal mountain glaciers: A 3-D thermal regime model for glaciers. *Journal of Geophysical Research: Earth Surface* 119(9): 1876–1893.

Gilbert A., Vincent C., Six D., Wagnon P., Piard L., and Ginot P. (2014b). Modeling near-surface firn temperature in a cold accumulation zone (Col du Dôme, French Alps): from a physical to a semi-parameterized approach. *The Cryosphere* 8(2): 689–703.

Gilbert A., Vincent C., Gagliardini O., Krug J., and Berthier E. (2015). Assessment of thermal change in cold avalanching glaciers in relation to climate warming. *Geophysical Research Letters* 42(15): 6382–6390.

Gilbert A., Wagnon P., Vincent C., Ginot P., and Funk M. (2010). Atmospheric warming at a high-elevation tropical site revealed by englacial temperatures at Illimani, Bolivia (6340 m above sea level, 16°S, 67°W). *Journal of Geophysical Research* 115(D10): D10109.

Haeberli W., and Beniston M. (1998). Climate Change and Its Impacts on Glaciers and Permafrost in the Alps. *Ambio* 27(4,): 258–265.

Harper J., Humphrey N., Pfeffer W. T., Brown J., and Fettweis X. (2012). Greenland ice-sheet contribution to sea-level rise buffered by meltwater storage in firn. *Nature* 491(7423): 240–243.

Hoelzle M., Darms G., Lüthi M. P., and Suter S. (2011). Evidence of accelerated englacial warming in the Monte Rosa area, Switzerland/Italy. *The Cryosphere* 5(1): 231–243.

Jenk T. M., Szidat S., Schwikowski M., Gäggeler H. W., Brütsch S., Wacker L., Synal H.-A., and Saurer M. (2006). Radiocarbon analysis in an Alpine ice core: record of anthropogenic and biogenic contributions to carbonaceous aerosols in the past (1650–1940). *Atmospheric Chemistry and Physics* 6(12): 5381–5390.

Konrad H., Bohleber P., Wagenbach D., Vincent C., and Eisen O. (2013). Determining the age distribution of Colle Gnifetti, Monte Rosa, Swiss Alps, by combining ice cores, ground-penetrating radar and a simple flow model. *Journal of Glaciology* 59(213): 179–189.

Koppal S.J. (2014). Lambertian Reflectance. In: Ikeuchi K. (eds) *Computer Vision*. Springer, Boston, MA. https://doi.org/10.1007/978-0-387-31439-6_534

Kuipers Munneke P., van den Broeke M. R., Reijmer C. H., Helsen M. M., Boot W., Schneebeli M., and Steffen K. (2009). The role of radiation penetration in the energy budget of the snowpack at Summit, Greenland. *The Cryosphere* 3(2): 155–165.

Kuipers Munneke P., M. Ligtenberg S. R., van den Broeke M. R., van Angelen J. H., and Forster R. R. (2014). Explaining the presence of perennial liquid water bodies in the firn of the Greenland Ice Sheet. *Geophysical Research Letters* 41(2): 476–483.

Legrand M., Preunkert S., May B., Guilhermet J., Hoffman H., and Wagenbach D. (2013). Major 20th century changes of the content and chemical speciation of organic carbon archived in Alpine ice cores: Implications for the long-term change of organic aerosol over Europe. *Journal of Geophysical Research: Atmospheres* 118(9): 3879–3890.

Licciulli C, Bohleber P, Lier J, Gagliardini O, Hoelzle M, Eisen O (2020). A full Stokes ice-flow model to assist the interpretation of millennial-scale ice cores at the high-Alpine drilling site Colle Gnifetti, Swiss/Italian Alps. *Journal of Glaciology* 66(255), 35–48.

Lier, J. (2018). Estimating the amount of latent heat released by refreezing surface melt water for the high-Alpine glacier saddle Colle Gnifetti, Swiss/Italian Alps, Master’s thesis, University of Heidelberg.

Ligtenberg S. R. M., Helsen M. M., and van den Broeke M. R. (2011). An improved semi-empirical model for the densification of Antarctic firn. *The Cryosphere* 5(4): 809–819.

Lüthi D., Le Floch M., Bereiter B., Blunier T., Barnola J.-M., Siegenthaler U., Raynaud D., Jouzel J., Fischer H., Kawamura K., and Stocker T. F. (2008). High-resolution carbon dioxide concentration record 650,000–800,000 years before present. *Nature* 453(7193): 379–382.

Marchenko S., van Pelt W.J.J., Claremar B., Pohjola V., Pettersson R., Machguth H., and Reijmer C. (2017). Parameterizing Deep Water Percolation Improves Subsurface Temperature Simulations by a Multilayer Firn Model. *Frontiers in Earth Science* 5. https://doi.org/10.3389/feart.2017.00016.

Masson-Delmotte V., Dreyfus G., Braconnot P., Johnsen S., Jouzel J., Kageyama M., Landais A., Loutre M.-F., Nouet J., Parrenin F., Raynaud D., Stenni B., and Tuenter E. (2006). Past temperature reconstructions from deep ice cores: relevance for future climate change. *Climate of the Past* 2(2): 145–165.

Preunkert S., Legrand M., and Wagenbach D. (2001). Sulfate trends in a Col du Dôme (French Alps) ice core: A record of anthropogenic sulfate levels in the European midtroposphere over the twentieth century. *Journal of Geophysical Research: Atmospheres* 106(D23): 31991–32004.

Schneider T., and Jansson P. (2004). Internal accumulation in firn and its significance for the mass balance of Storglaciären, Sweden. *Journal of Glaciology* 50(168): 25–34.

Shumskii P. A. (1964). *Principles of Structural Glaciology: The Petrography of Fresh-water Ice as a Method of Glaciological Investigation*. New York: Dover Publications Inc.

Sturm M., Holmgren J., König M., and Morris K. (1997). The thermal conductivity of seasonal snow. *Journal of Glaciology* 43(143): 26–41.

Suter S., Laternser M., Haeberli W., Frauenfelder R., and Hoelzle M. (2001). Cold firn and ice of high-altitude glaciers in the Alps: measurements and distribution modelling. *Journal of Glaciology* 47(156): 85–96.

Thevenon F., Anselmetti F. S., Bernasconi S. M., and Schwikowski M. (2009). Mineral dust and elemental black carbon records from an Alpine ice core (Colle Gnifetti glacier) over the last millennium. *Journal of Geophysical Research* 114(D17): D17102.

van Pelt W. J. J., Oerlemans J., Reijmer C. H., Pohjola V. A., Pettersson R., and van Angelen J. H. (2012). Simulating melt, runoff and refreezing on Nordenskiöldbreen, Svalbard, using a coupled snow and energy balance model. *The Cryosphere* 6(3): 641–659.

van Pelt W. J., and Kohler J. (2015). Modelling the long-term mass balance and firn evolution of glaciers around Kongsfjorden, Svalbard. *Journal of Glaciology* 61(228): 731–744.

van Pelt W., Pohjola V., Pettersson R., Marchenko S., Kohler J., Luks B., Hagen J. O., Schuler T. V., Dunse T., Noël B., and Reijmer C. (2019). A long-term dataset of climatic mass balance, snow conditions, and runoff in Svalbard (1957–2018), *The Cryosphere* 13: 2259–2280, https://doi.org/10.5194/tc-13-2259-2019.

Vandecrux B., Fausto R. S., van As D., Colgan W., Langen P. L., Haubner K., Ingeman-Nielsen T., Heilig A., Stevens C. M., MacFerrin M., Niwano M., Steffen K., and Box J. E. (2020). Firn cold content evolution at nine sites on the Greenland ice sheet between 1998 and 2017. *Journal of Glaciology* 66(258): 591–602.

Vincent C., Gilbert A., Jourdain B., Piard L., Ginot P., Mikhalenko V., Possenti P., Le Meur E., Laarman O., and Six D. (2020). Strong changes in englacial temperatures despite insignificant changes in ice thickness at Dôme du Gôuter glacier (Mont Blanc area). *The Cryosphere* 14(3): 925–934.

Vincent C., Le Meur E., Six D., Possenti P., Lefebvre E., and Funk M. (2007). Climate warming revealed by englacial temperatures at Col du Dôme (4250 m, Mont Blanc area). *Geophysical Research Letters* 34(16).

Wagenbach D., Bohleber P., and Preunkert S. (2012). Cold, alpine ice bodies revisited: what may we learn from their impurity and isotope content? *Geografiska Annaler: Series A, Physical Geography* 94(2): 245–263.

Warren S. G. (1982). Optical properties of snow. *Reviews of Geophysics* 20(1): 67.

Wolff E. W., Barbante C., Becagli S., Bigler M., Boutron C. F., Castellano E., de Angelis M., Federer U., Fischer H., Fundel F., Hansson M., Hutterli M., Jonsell U., Karlin T., Kaufmann P., Lambert F., Littot G. C., Mulvaney R., Röthlisberger R., Ruth U., Severi M., Siggaard-Andersen M. L., Sime L. C., Steffensen J. P., Stocker T. F., Traversi R., Twarloh B., Udisti R., Wagenbach D., and Wegner A. (2010). Changes in environment over the last 800,000 years from chemical analysis of the EPICA Dome C ice core. *Quaternary Science Reviews* 29(1–2): 285–295.

Yen Y.-C. (1981). *Review of thermal properties of snow, ice and sea ice*. no. 81–10. DTIC.